DEPARTMENT OF TRANSPORTATION

Evaluation of Work Zone Safety Using the SHRP2 Naturalistic Driving Study Data – Volume 2 Description of Research

Shauna Hallmark, Principal Investigator
Institute for Transportation
Iowa State University

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TOOLS FOR THE ROAD AHEAD

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16. Abstract (Limit: 250 words)

This report is one of the deliverables for the culmination of several phases of a project, which evaluated driver behavior in work zones using the SHRP2 Naturalistic Driving Study (NDS) data. This study utilized SHRP2 NDS to evaluate the impact of traffic control devices in reducing driver speed in work zones. The main advantage to the SHPR 2 NDS data is that on-road driver behavior was captured and can be used to evaluate how drivers behave in various situations. The study included four different analyses. The first evaluated where drivers began reacting to various work zone traffic control devices. The second assessed how drivers changed speed upstream to immediately downstream as they encountered various traffic control devices. The third assessed how drivers react when they encounter the back of a queue and the fourth developed speed based on work zone characteristics such as presence of barriers.

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Prepared by:

Shauna Hallmark, Guillermo Basulto-Elias, Nicole Oneyear, Omar Smadi
Institute for Transportation at Iowa State University
Susan Chrysler, Gerald Ullman
Independent Contractors

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Technical Advisory Panel Members include:

- Ken Johnson, MnDOT Assistant State Traffic Engineer
- Brad Estochen, former MnDOT State Traffic Safety Engineer
- Ron Rauchle, MnDOT Metro District Work Zone Engineer
- Jeffrey Morey, MnDOT Work Zone Standards Specialist
- Steve Blaufuss, Statewide Maintenance Work Zone & Operations Specialist
- Jason Spilak, FHWA Project Development Engineer
- Ted Ulven, MnDOT Work Zone Safety Training Supervisor
- Derek Leuer, MnDOT Administrative Engineer
- Michelle Moser, MnDOT State Work Zone Engineer
- Tiffany Dagon, Metro District Work Zone Engineer
- Ken Hansen; District Traffic Engineer for District 3

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CHAPTER 1: EXECUTIVE SUMMARY

1.1 BACKGROUND

In 2017 a total of 710 fatal work zone crashes occurred accounting for 1.7% of all fatal roadway crashes in the US (710 of 42,231) in 2017. Additionally, 94,000 total crashes and 25,000 injury crashes occurred in work zones in 2017. Moreover, work zone fatalities on US roads increased by 3.2% from 2016 to 2017 (NWZSIC 2019). Work zone crashes are not only a problem for the traveling public, but they are also a serious concern for highway workers who are injured or killed by errant vehicles. A total of 132 work zone worker fatalities occurred in 2017 (NWZSIC 2019) and 60% of worker fatalities were struck by vehicles in the work zone (CDC 2020). Consequently, addressing work zone crashes is critical for both the traveling public and highway workers. Statistics are provided for 2017 since that is the most recent year for which all of the above reported statistics were consistently available.

Work zone crashes are caused by a variety of factors, such as driver error, driver distraction, inadequate visibility, poor road surface conditions, roadway obstructions, inadequate traffic control, and improper management of material, equipment, and personnel in work zones. Many crashes result from unsafe behavior, such as failure to yield or traveling at unsafe speeds.

Work zone crashes occur at different rates in different types of work zones. Akepati and Dissanayake (2011) determined that 37% of work zones crashes in two Midwestern states occurred during a lane closure; 18% occurred during work on the shoulder or median; 15% occurred when there was a lane shift, crossover, and/or head-to-head traffic; and 8.7% occurred at intermittent or moving work zones.

1.2 PROJECT OBJECTIVES

The project was funded by the Federal Highway Administration Implementation Assistance Program (IAP) and was managed and co-sponsored by the Minnesota Department of Transportation (MnDOT). Phase I conducted a proof of concept using the SHRP2 data to assess driver behavior in work zones. Phase II utilized the data to assess driver behavior in work zones on 4-lane and multi-lane roadways. Phase III increased the sample of drivers who were using cell phones and updated the statistical methods developed in Phases I and II. Phase III also focused on implementation.

Volume 1 summarizes the effectiveness of different work zone countermeasures in reducing speed or crashes in the form of toolbox. Information from a literature review as well as the analyses conducted for this project are summarized by countermeasures in a format which is useful for practitioners seeking information.

This report (Volume 2) provides a more detailed description of the research results is provided in Volume 2. This includes a summary of the data collection, data reduction, statistical methods used and findings.

1.3 DATA UTILIZED

Potential work zones were identified in five of the six NDS study states using the 511 data collected as part of the Roadway Information Database (RID) developed by the Center for Transportation Research and Education (CTRE) at Iowa State University (ISU) (511 data were not available for Indiana). Potential locations were further reduced to include only those work zones estimated to have lasted 3 or more days. A minimum of 3 days was used to ensure that multiple time series traces could be identified for a particular work zone. Next, a distance upstream and downstream of each work zone was established to encapsulate the work zone's extent, and the Virginia Tech Transportation Institute (VTTI) provided several time series traces along the identified segments. These segments were reviewed, and only those where an active work zone was present were included as work zones of interest. Although more descriptive criteria were used to define "active" work zones, this was essentially considered to be a work zone with a lane or shoulder closure. Once a final set of active work zones was identified, the work zone extents were further defined, and time series traces through each work zone were requested.

Once the traces were received, data reductionists coded the characteristics of the work zones. Since a work zone can change even from day to day, work zone features had to be manually extracted for each time series trace, which required a significant amount of resources. Data were requested for two-lane, four-lane, and multi-lane facilities. However, few two-lane roadways with work zones were ultimately identified, and as a result work zones on this type of roadway were not ultimately included in the analyses with the back of queue analysis which included events for all roadways types. Work zone features were correlated to the time series traces. Consequently, the position of a driver/vehicle from a work zone feature at any point could be determined. The legibility distance for each sign was calculated using the *Manual on Uniform Traffic Control Devices* (MUTCD) and other research as a reference. Legibility distance was used to estimate the point at which a driver would be able to see a sign or other work zone feature, and it was assumed that some reaction would take place within that area.

Pre-work zone roadway conditions were also coded using the RID, the forward video view in the NDS data, or aerial views of the roadway. These conditions included characteristics such as number of lanes, type of median, etc. Weather conditions (dry, rain) were also coded. Finally, driver glance behavior and presence of a distraction were coded by either the research team or VTTI data reductionists. Due to the cost of reducing driver face video, only 1,099 traces were reduced. In a few cases, time series traces were utilized where the driver characteristics had not been reduced. In these cases, driver characteristics were not included in the corresponding model.

The work zone was divided into functional areas. The work zone was assumed to officially start at the taper point for the shoulder or lane closure. The work zone extent was defined as the distance from the taper point to the point where the lane/shoulder closure ended, and normal traffic operations resumed. The area upstream of the taper point to the first work zone sign was termed as the work zone influence area. Further upstream, it was assumed that normal traffic operations were in effect.

1.4 SUMMARY OF ANALYSES

Several different analyses were conducted to assess the data from different perspectives. Each analysis is summarized below.

1.4.1 Work Zone Reaction Point

This analysis is detailed in Chapter 3 and estimated whether drivers reacted within the influence area of various work zone features in the advance warning area with a focus on work zones on 4-lane roadways. A change point model was used to detect the points along each time series trace where drivers reduced their speed by ≥ 3 mph with normal deceleration. These change points were surrogates for driver reaction and were mapped to the legibility area of each work zone feature. A mixed effects logistic regression model was developed, and the likelihood of a driver's response to each work zone feature was estimated.

Drivers were 6.04 times more likely to respond when a work zone speed limit sign was present and were 5.07 times more likely to respond when the speed limit sign included a dynamic speed feedback sign than for a regular static work zone sign. Drivers were 2.42 times more likely to react when an active CMS was present compared to a regular static work zone sign. When the CMS was inactive, drivers were 1.45 times more likely to react, but the difference was not statistically significant. When a "Lane Ends" sign was present drivers were 1.64 times more likely to respond than for a static work zone sign.

In general, the farther a driver was from the start of the work zone, the less likely they were to show a response for most types of traffic control devices. For each 100 meters farther away they were, a driver was 0.97 times less likely to respond. However, the opposite effect was noted, the farther a speed limit sign was placed from the start of work zone, the more likely a driver was to respond (OR = 1.05 with every 100 meters increase in distance).

Drivers who were traveling over the speed limit were more likely to show a response than drivers traveling at or below the speed limit. The odds of a driver showing response increased by 1.06 times with every one mile per hour increase in driving speed over the posted speed limit. This makes sense as drivers who were traveling at or near the speed limit did not necessarily need to respond.

1.4.2 Change in Speed

This analysis evaluated driver behavior from a different perspective than the change point analysis. In this case, the driver's change in speed was measured from a point upstream of the legibility distance of traffic control device (TCD) to a point just past the device. The intent was to determine whether drivers slowed down for particular features. A full description is provided in Chapter 4.

A linear mixed effects model was used to predict drivers' change in speed as they encountered a particular TCD within the work zone. Change in speed was calculated within the influence area of each work zone traffic control device for each time series trace. This included and TCD within 2.5 miles upstream of the taper point to a distance 1.0 mile inside the work zone (downstream).

Initial models were developed for work zones on four-lane and multi-lane roadways. However, the results were similar, and they were combined into a single model. The final model indicated dynamic speed feedback signs were the most effective traffic control devices in terms of eliciting a change in speed with an average decrease of 4.0 mph. When drivers encountered an arrowboard, they decreased speed by 2.8 mph. Decreases of 2.2 mph were estimated for trailer mounted changeable message signs. The status of overhead changeable message signs (active versus not active) was modeled separately. Overhead message signs are not necessarily related to the work zone (i.e., Message Monday) but were included since it was felt it may have an impact on speed. When an overhead CMS was active, a reduction of 1.2 mph was noted and when not active a reduction of 0.5 mph resulted. The results for “not active” were not statistically significant but were presented for completeness since the results for active were significant.

Presence of a lane merge sign resulted in a 1.9 mph decrease in speed. A reduction of 1.4 mph was noted when a driver encountered an enforcement sign. This category included any sign which indicated penalties such as “Fines Doubled” or “Speeding Fines Increased.” It should be noted, this change was due to presence of the physical sign. Evaluating the speed impacts of policies for higher fines within work zones was not within the scope of this project.

Both regular speed limit and enforcement speed limit sign resulted in a 2.3 mph decrease in speeds. When drivers encountered any other type of sign, a reduction of 1.8 mph was noted. The category of “Other” covers any other static work zone sign not included in the categories discussed above. This would include signs such as “Work Zone Ahead”, “Work Zone Ends”, “Lane Shift”, “Shoulder Work,” etc.

1.4.3 Back-of-Queue Behavior

The majority of rear end crashes occur at the back of a queue. A line of stopped or slowed traffic is common in work zones, and safety issues may arise when drivers are not paying attention or misjudge the forward vehicles’ speed. As a result, driver behavior at the back of the queue was evaluated as described in Chapter 5.

Back of queue scenarios were identified through a review of safety critical events (SCE) in work zones coded by the Virginia Tech Transportation Institute (crashes, near crashes, or conflicts) as well as a review of time series traces in work zones collected for a related project. This resulted in 46 safety critical events and 283 “normal” events. A mixed Mixed-Effects Logistic Regression model was developed with odds of an SCE as the response variable.

A simplistic comparison of the data indicated 28% of drivers involved in a back of queue SCE were using a cell phone compared to 5% of driver in the baseline. Hence, drivers involved in an SCE were more than 5 times more likely to be engaged in a cell phone task as those involved in a “normal” back of queue event. This was not ultimately included as statistically significant in the final model due to sample size.

The final model indicated, involvement in an SCE was 3.8 more likely if the driver was engaged in a glance away from the roadway task of 1 or more seconds ($p = 0.0147$). When a driver is following closely (< 2 seconds) they are 2.91 times more likely to be involved in an SCE ($p = 0.0568$) than when not following. Drivers following another vehicle (within 2 to 3 seconds) are less likely to be involved in an SCE, but this difference was not statistically significant (p = 0.6003) and was only included in the model since other conditions for following were included.

1.4.4 Evaluation of Speed Profiles in Work Zones

An analysis was conducted to evaluate the impact of various work zone and driver characteristics on speed selection through the work zone. A set of active work zones on 4-lane and multi-lane roads were identified and time series data obtained for a range of drivers. A profile of vehicle speeds was developed at five points within the work zones (500 and 250 m upstream, at the work zone start point, 250 and 500 m downstream).

Time series traces (879) representing 407 unique drivers over 112 different work zones on multi-lane and 4-lane roadways were evaluated. Speed profiles at five points upstream and within work zones were developed and compared across relevant characteristics using a multivariate regression model. The model fit a speed profile for each section simultaneously, creating a speed profile over the 5 points. Separate models were developed for work zones on 4-lane and multi-lane roadways.

Results for the 4-lane model indicate the work zone configuration, combination of median type upstream and barrier type within the work zone, glances away from the driving task over 1 second, and cell phone use were statistically significant. The same variables were statistically significant for the multi-lane model, but time of day and weather conditions were also relevant.

1.4.5 Limitations

Although every attempt was made to account for issues in the data and to ensure that the sample size was adequate, several limitations remained that may have influenced the results of the analyses. These limitations are summarized as follows:

- Sample size may have been an issue. Although over 1,000 traces were ultimately available, they represented several different work zone configurations. Since work zones are complicated and have a number of varying characteristics, it was difficult to gather enough samples to adequately represent all work zone features. Additionally, driver distraction was of significant interest. Since there was no method to detect driver distraction or cell phone use in the raw time series data, it was difficult to ensure that adequate samples of these behaviors were present. Further reduction of data was not feasible due to time and resource constraints.

- Work zones lasting three or more days were selected for analysis. This was to ensure that several time series traces would be available through the work zone. However, the longer a work zone was in place, the more likely drivers were aware of the work zone conditions and reacted accordingly. For instance, drivers may have slowed before particular work zone features because they were anticipating changing conditions in the work zone rather than reacting to particular work zone features.

- Work zones are complicated entities. Even with a sample of several hundred observations, the myriad complex features of work zones make it difficult to isolate the impact of a specific feature or set of features.
- NDS data have a certain amount of noise. For instance, speed data exhibit a number of fluctuations within short time periods that appear to represent acceleration/deceleration but in actuality are fluctuations in sensor measurements. As a result, predicting driver reactions based on speed changes can be challenging.

CHAPTER 2: DESCRIPTION OF DATA

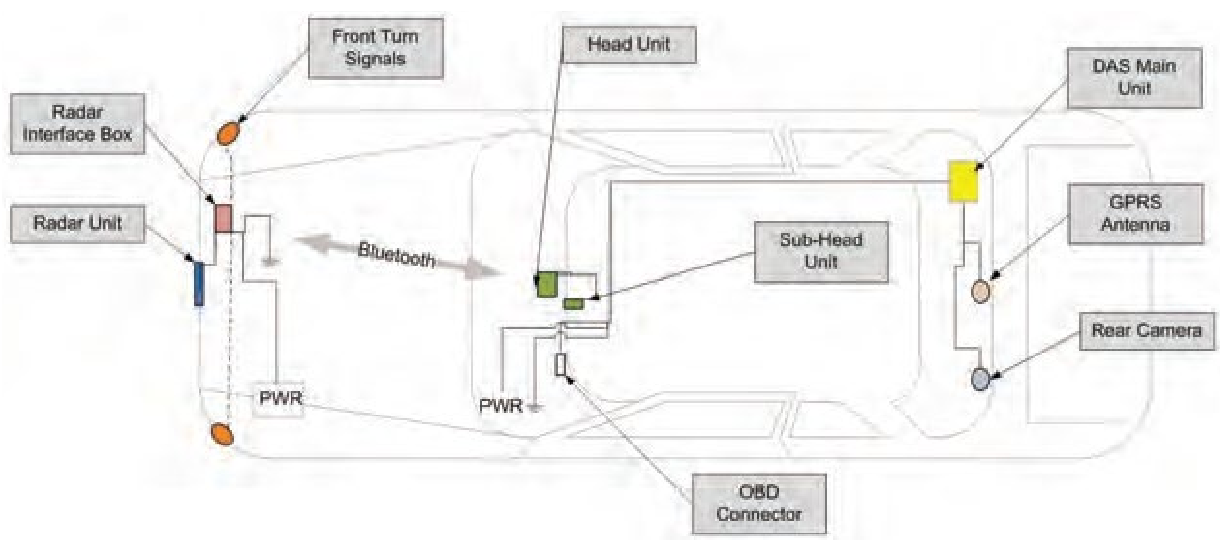
2.1 SOURCE OF DATA

2.1.1 Naturalistic Driving Study Data

The naturalistic driving study (NDS) performed under the Strategic Highway Research Program 2 (SHRP2) is the largest and most comprehensive NDS undertaken to date (in the US or elsewhere). Data were collected from over 3,000 male and female volunteer passenger vehicle drivers, ages 16 to 98, with most drivers participating between one and two years. Data were collected from sites in six US states: Florida, Indiana, New York, North Carolina, Pennsylvania, and Washington. The NDS data file contains about 50 million vehicle miles, 5 million trips, and more than 3,900 vehicle-years, for a total of about 2 petabytes of data.

The study was conducted from October 2010 to November 2013 (Dingus et al. 2014). In-vehicle data were collected via a data acquisition system (DAS). A large amount of vehicle kinematic information was captured, including speed, acceleration, and braking; forward radar; and multiple video views, including the forward roadway, the rear roadway, the driver's face, and over the driver's shoulder. Global positioning system (GPS) data were also collected and associated with the vehicle activity data so driving traces could be overlain with roadway or other spatial data. Most kinematic vehicle variables are reported at 0.1-second intervals.

The SHRP NDS data are stored at a secure data enclave at VTTI, which is located in Blacksburg, Virginia. Figure 2.1 shows the framework of the DAS for the SHRP2 NDS project, including the placement of various units.



DAS=data acquisition system, GPRS=general packet radio service, OBD=on-board diagnostic, PWR=power supply unit
Campbell 2012, TR News

Figure 2.1. Framework of SHRP2 NDS data acquisition system

For the present study, NDS data were provided as in a time series trace database (.csv file). Each of these represents the data in 0.1-second intervals for one trip for one driver through one work zone. A video clip of the forward roadway and a video clip of the rear roadway were also provided for each time series trace. The driver videos could only be reviewed at the VTTI secure data enclave.

2.1.2 Roadway Information Database

The RID was developed by the Center for Transportation Research and Education (CTRE) at the Institute for Transportation (InTrans) at Iowa State University (ISU). A mobile data collection van was used to collect about 12,500 centerline miles in the six SHRP2 NDS states. Roadway features collected included curve radius, number of lanes, roadway alignment, signing, presence and type of intersections, lane width, grade, shoulder types, and lighting. In the present study, RID data were linked to the NDS data.

The NDS data can be also linked to other roadway databases or aerial imagery to extract additional roadway features. Other data were collected and incorporated into the RID. These data came from several sources, including the NDS states' respective departments of transportation (DOT) and the Federal Highway Administration's (FHWA's) Highway Performance Monitoring System (HPMS); these sources cover most roadways for each study state. In addition, supplemental data such as 511 data, construction project data, crash data, and traffic volume data were also collected.

2.2 IDENTIFICATION OF WORK ZONES

Data collection for this study entailed determining work zone locations within the SHRP2 NDS data. The steps taken to identify work zones and request data for project purposes are summarized below.

2.2.1 Step 1: Identify Potential Work Zones Using 511 Data

The 511 data served as the main source of information to identify work zone events for this study. The 511 system is a resource for national travelers which is set up and run by the United States DOT and FHWA. Currently 35 states participate in the 511 system. The system allows drivers to dial "511" on their phones and receive real-time traffic information, such as the road closures, crashes, detours, and other alerts.

The 511 data for the time period coincident with the SHRP 2 NDS data collection (2011 to 2013) were queried for construction related terms such as "construction", "lane closure", "road work", "maintenance". Potential work zones were flagged and then those which were in place for more than three days retained. Three days was used as a threshold because it was unlikely that a sufficient number of NDS time series traces would be available for short-duration work zones.

No specific field in the RID supplemental 511 data could identify work zones, but the fields representing event type and event description provided information about any construction or maintenance activities. Therefore, an attribute query was conducted using ArcGIS to identify potential work zones. Key words such as "construction," "lane closure," "road work," or "maintenance" were used. This query was different for different states due to the disparity in 511 data among states. Table 2.1 shows the details of the 511 files and attribute queries.

Table 2.1. Available attribute fields for identifying work zones by state

NDS States	RID 511 Files Used	Attribute Query for Work Zones in ArcGIS	Text Search Attribute for Work Zone Configuration
Washington (WA)	Point features: Events511_Points_2011, Events511_Points_2012, Events511_Points_2013	EVENTCATEG = 'Construction' OR 'Lane Closure' OR 'Maintenance'	"HEADLINEDE"
	Line features: Events511_Lines_2011, Events511_Lines_2012, Events511_Lines_2013		
Florida (FL)	Point features: ATMSIncidents2011to2013	FDOT_EVENT_TYPE = 'Construction'	"EVENT_NM"
North Carolina (NC)	Line features: TIMS_NC.	No field available to create attribute query	"REASON"
New York (NY)	Point features: Events511_2010, Events511_2011, Events511_2012, Events511_2013	EVENT_TYPE = 'Construction' OR 'Lane Closure' OR 'Maintenance'	"EVENT_DESC"
Pennsylvania (PA)	Line features: Events511_Lines_2011-2013	CAUSE= "ROADWORK"	"STATUS"

2.2.2 Step 2: Determine the Locations of Potential Work Zone Events and Obtain the Number of Likely Trips

The next step was to link the potential work zone events identified in the 511 data to the RID links. In some cases, the 511 data were in the form of a single point for each event, which did not indicate work zone extent, or in the form of a line. Figure 2.2 (left) shows 511 line data for Washington State, and Figure 2.2 (right) shows 511 point data for New York State.

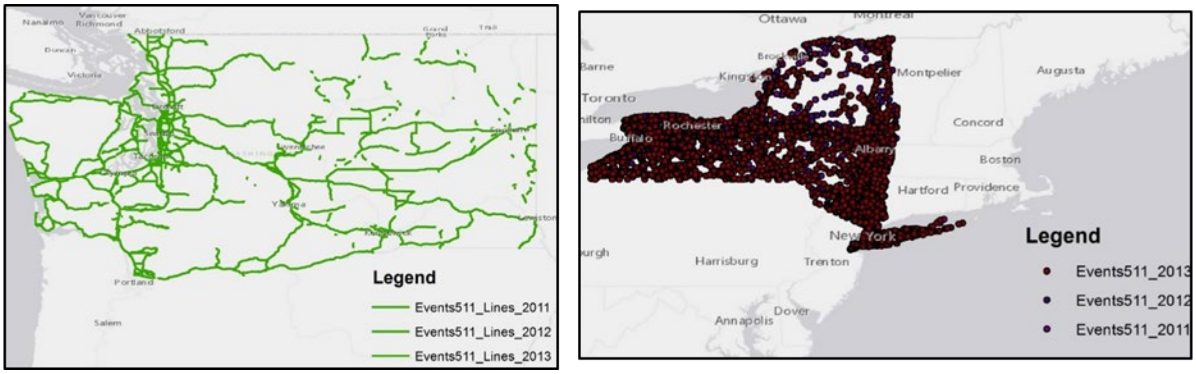


Figure 2.2. 511 point (left) versus line (right) events

When 511 events were provided as lines, the lines were associated with links in the RID. In order to locate the links that directly intersected the 511 events, a dynamic segmentation method was utilized. An estimate of the work zone extents was assumed using the corresponding RID links. When 511 events were provided as points, each point was mapped to the RID, and the nearest corresponding link ID was extracted. Dynamic segmentation was used to extract links two miles upstream and downstream of the point.

Next, start and end dates were used to select work zones that lasted more than three days. A minimum of three days was used to ensure that multiple time series traces could be identified for a particular work zone. This narrowed the sample of potential work zones by a significant amount. A total of 9,290 work zones lasting three or more days were identified for the five NDS states included in the study, as shown in Figure 2.3. Indiana was not included because 511 data were not available for that state.

Image source: ESRI; Data source: VTTI

Figure 2.3. Locations of potential work zones

The estimated extents of the work zones were sent to VTTI, and the number of time series traces and unique drivers and the drivers' age/gender information for the links of interest were requested. Potential work zone trips were determined by identifying the trips falling within the dates indicated in the 511 data. VTTI provided a list of potential trips and unique drivers and the age/gender of each driver. Table 2.2 shows the number of trips and unique drivers available in each state.

Table 2.2. Descriptive statistics of trips and participants for potential work zones in each state

State	Total No. of Work Zones	Trip Counts			Participants		
		Mean	Min	Max	Mean	Min	Max
North Carolina	90	500.9	32	7,715	91.37	11	410
Florida	39	1,026.13	34	9,056	124.5	17	579
New York	1,748	2,033.86	31	23,187	127.4	11	665
Washington	6,984	2,267.99	31	13,097	193.1	11	665
Pennsylvania	429	307.25	31	11,836	58.14	11	224

As the table shows, 90 of the 9,290 potential work zones were in North Carolina, with an average of 501 trips per work zone. An average of 91 unique drivers per work zone was also available in North Carolina.

2.2.3 Step 3: Refine the Extents of Potential Work Zones

The data set resulting from Step 2 was reviewed, and work zones with at least 15 NDS time series traces were selected, resulting in 1,680 potential work zones. About 7,220 work zones in the initial data set had fewer than 10 trips and were not utilized.

In order to request time series traces, it was necessary to make some estimate of the actual physical extent of each potential work zone. When 511 data were presented as a link, the link was mapped to the RID and the corresponding link IDs extracted. Dynamic segmentation was then used to add links approximately 0.5 miles upstream and downstream of each identified work zone to increase the likelihood that the actual work zone was included. When 511 data were presented as points, dynamic segmentation was used to extract links 2 miles upstream and downstream of each point.

2.2.4 Step 4: Confirm Work Zone Presence and Duration

A list of link IDs and work zone dates was submitted to VTTI. Several time series traces and forward videos were requested for each of the 1,680 work zones identified in Step 3. Multiple traces were requested because information about start and end times in the 511 data were not always accurate, work zones did not always start or end on time, and 511 records were not always updated.

About 3,000 traces were received, and the forward videos were reviewed to determine whether a work zone was actually present and whether the work zone was active. In some cases, no work zone was present. Work zones that contained signals or other interruptions in traffic flow were excluded because predicting speed or reaction point would have been difficult in these situations.

The next step was to determine whether the remaining work zones were active since scenarios such as a set of barrels or cones along the side of a roadway did not represent the type of work zones that were of interest to the project team and technical advisory committee (TAC). An active work zone was defined as having one of the following characteristics: lane closure, shoulder closure, workers present, or equipment present. Ultimately, all work zones included in the analyses had a shoulder or lane closure.

2.2.5 Step 5: Identify Work Zones Using Near-Crashes

Another method to identify potential work zones was through construction-related near-crashes. A list of safety critical events including crashes and near-crashes was available through the SHRP2 InSight website. Crashes were not included in the analyses since location could not be provided due to privacy constraints. Each of the available near-crashes was reviewed using the tools on the InSight webpage, including the forward video clip and other characteristics available for each near-crash event. Near-crashes in work zone locations that met the criteria used in Step 4 were flagged. A time series trace and forward video through each identified location was requested for each near-crash to confirm whether the location met the criteria specified in previous steps.

2.2.6 Step 6: Request Final Data Sets

Using the process described in Steps 4 and 5, about 240 viable work zones were identified that included four-lane, multi-lane, or two-lane roadways with shoulder or lane closures. The beginning and end points of each work zone that had initially been identified were adjusted based on a review of the forward video and corresponding spatial locations from the time series data. Once the beginning and end points were established, a distance 1 mile upstream and downstream of each work zone was determined using dynamic segmentation for the second time. All link IDs associated with the work zone and the upstream/downstream segments were extracted.

2.3 DATA REDUCTION

The following summarizes the general data reduction activities for this study. If additional data reduction was necessary for a particular analysis, it is detailed within the corresponding summary.

Raw NDS data were provided by VTTI in terms of events. Each event included one trip by one driver through a particular work zone. A time series trace was provided for each event in the form of a CSV file with information including a time stamp (data were provided at 0.1-second intervals), position, speed, forward acceleration, lateral acceleration, wiper position status, brake status, lane position variables, etc. A video clip showing the forward roadway and a video clip showing a rear roadway view were also provided. A video clip of the driver's face and hand positions was accessible at the VTTI secure data enclave and was utilized to reduce driver characteristics as noted in Section 2.3.4. About 10,000 time series traces were received.

Since the time series data can have missing observations, only time series traces that had more than 90% of speed data available were utilized in the study. After a review of the forward video, time series traces were further excluded when the forward video view was not clear; snow or adverse weather was present, or traffic control devices were present which controlled flow (i.e., traffic signals, flaggers). Initially work zones on 2-lane roadways were included but only a small number of these were ultimately available so for consistency only work zones on 4-lane or multi-lane roadways were utilized for most of the analyses.

This reduced the number of traces that were available to about 50%. Data were requested early in the project, and a number of lessons were learned as data were coded. As a result, in retrospect, the data request should have specified a threshold percentage of "good" speed data.

For the traces utilized, speed was occasionally missing for some intervals. Time series data are reported at 10 Hz (0.1-second intervals). When speed was missing for an interval, speed was interpolated using the nearest neighbor approach.

Each of the remaining time series traces was geocoded and matched to the corresponding roadway link in the RID, and roadway characteristics were extracted as noted in Section 2.3.1. Time of day (daytime, nighttime with no street lighting, nighttime with street lighting), ambient conditions (e.g., foggy), and pavement surface condition (e.g., wet, dry) were also coded. Work zone characteristics were also coded as noted in Section 2.3.2.

The number of available events was further reduced since some events either did not occur when the work zone was present or the configuration changed so that the work zone was no longer considered active. Additionally, traces for which the approximated traffic conditions were lower than Level of Service (LOS) C were also not used for most of the analyses since it was felt that most of the driver behaviors evaluated, such as speed, would be impacted by the behavior of surrounding vehicles. Events with congestion were utilized for the back-of-queue analysis.

Since work zone configuration can change from day to day, even for the same work zone, reduction of work zone characteristics could not be automated in any fashion and required manual data reduction. Additionally, reduction of driver face video was significantly time consuming for the team and was ultimately outsourced to VTTI. As a result, due to the actual cost or resources of data reduction, only a subset of the data could be reduced within project resources.

As a result, the events remaining after those meeting the previously described criteria had been selected were further sampled, e.g., traces with less than 90% of speed data. Sampling was done to represent both day and night as well as driver characteristic such as age and gender.

2.3.1 Roadway Characteristics

Non-work zone roadway characteristics of interest were extracted for each time series trace. When roadway characteristics could not be obtained from the RID data, they were extracted from Google Earth, the forward view video, or aerial images. Roadway characteristics included the following:

- Number of lanes
- Type of median
- Surface type (asphalt versus concrete)

- Shoulder type
- Speed limit
- Presence of lighting
- Number of uncontrolled intersecting roadways
- Presence and type of traffic control

2.3.2 Work Zone Characteristics

Work zone configuration and characteristics were coded using the forward view video and included the following:

- Type and location of barriers
- Number of closed lanes
- Presence and type of DMS or other intelligent transportation system (ITS) countermeasures
- Presence of workers
- Presence of equipment
- Lane shifts
- Temporary pavement markings

Figure 2.4 illustrates the components of a work zone.

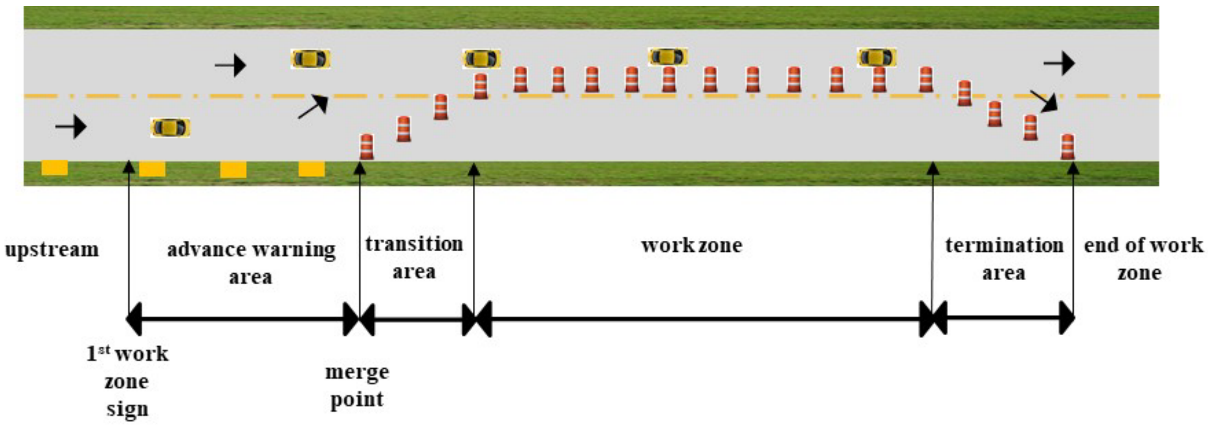


Figure 2.4. Schematic showing the components of a work zone

The start of the work zone influence area was indicated by the first work zone sign when available. This included any type of sign that alerts drivers to the presence of an upcoming work zone. In a few cases, signs were placed several miles upstream of a work zone and may not have been captured because the requested video trace was typically only 2 miles upstream of the merge point. In these cases, an area was assigned based on individual analysis needs.

The point between the first work zone sign and the merge point was referred to as the advance warning area and was characterized by various types of traffic control depending on the individual work zone, such as a reduced speed limit, changeable message signs, static signing, etc. (see Figure 2.5).

VTTI

Figure 2.5. Examples of identifying TCD in forward video

The work zone proper was considered to start at the beginning of the merge point until the transition away from the shoulder or lane closure at the termination area.

Examples of different types of signs are shown in Tables 2.3 and 2.4.

Table 2.3. Examples of static signs coded

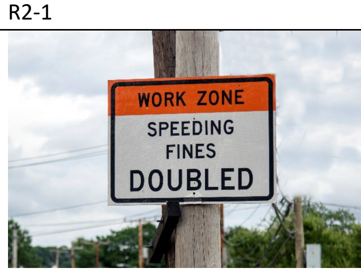
Type of Sign	Examples		
Standard work zone	 W21-5	 W20-1	 W20-5R-A
Work zone speed limit	 W3-5 RaksyBH, Shutterstock	 RaksyBH, Shutterstock	
Regular speed limit	 R2-1		
Work zone enforcement	 Solomon Kraner, Shutterstock		
Lane closure	 W4-2		

Image sources: FHWA 2019 MUTCD, unless otherwise credited

Table 2.4. Examples of dynamic signs coded

Type of Sign	Examples
Dynamic arrow board	 rustycanuck, Shutterstock
Trailer-mounted changeable message sign	 mikeledray, Shutterstock
Speed feedback sign	 Iowa DOT
Overhead changeable message sign	 rawf8, Shutterstock

The types of barriers were also coded with examples provided in Table 2.5.

Table 2.5. Examples of barriers/channelizers

Device	Examples	
Cones/panels	 F Armstrong Photography, Shutterstock	 F Armstrong Photography, Shutterstock
Barrels	 Kent Weakley, Shutterstock	
Concrete barrier	 Traffic camera	

2.3.3 Locating Features within Time Series Traces

Time series data were extracted for the distance from the start of the work zone to a point 200 meters upstream of the first work zone sign, as shown in Figure 2.6.

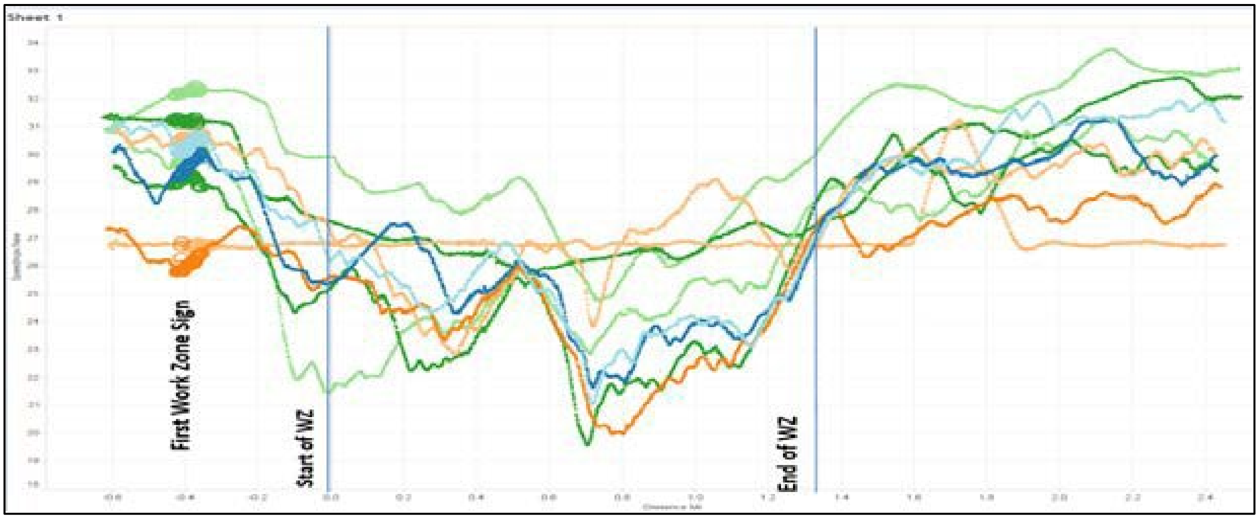


Figure 2.6. Time series traces in relation to work zone features

Because work zone configurations differed, the analysis distance differed accordingly. As noted previously, in a few cases the first work zone sign was placed several miles upstream of the work zone and was not captured in the time series traces for that work zone

The location of relevant roadway and work zone characteristics, such as signs or merge points, were coded in relation to vehicle position in the time series traces. Features such as work zone traffic control devices or the start of the work zone were identified in the forward video and then spatially located by noting the nearest video time stamp. The time stamps were physically located using the most proximate GPS records (latitude/longitude) and interpolation. As a result, the vehicle's position relative to each work zone feature (e.g., 200 meters upstream of the work zone merge point) was calculated and added as a variable in each row of the corresponding time series trace for each work zone trip (at 0.1-meter intervals). Using this information, a vehicle's position relative to any roadway feature could be determined. Figure 2-6 illustrates several time series traces plotted in relation to a variable message sign (VMS), the start of the work zone, and the end of the work zone.

2.3.4 Driver Characteristics

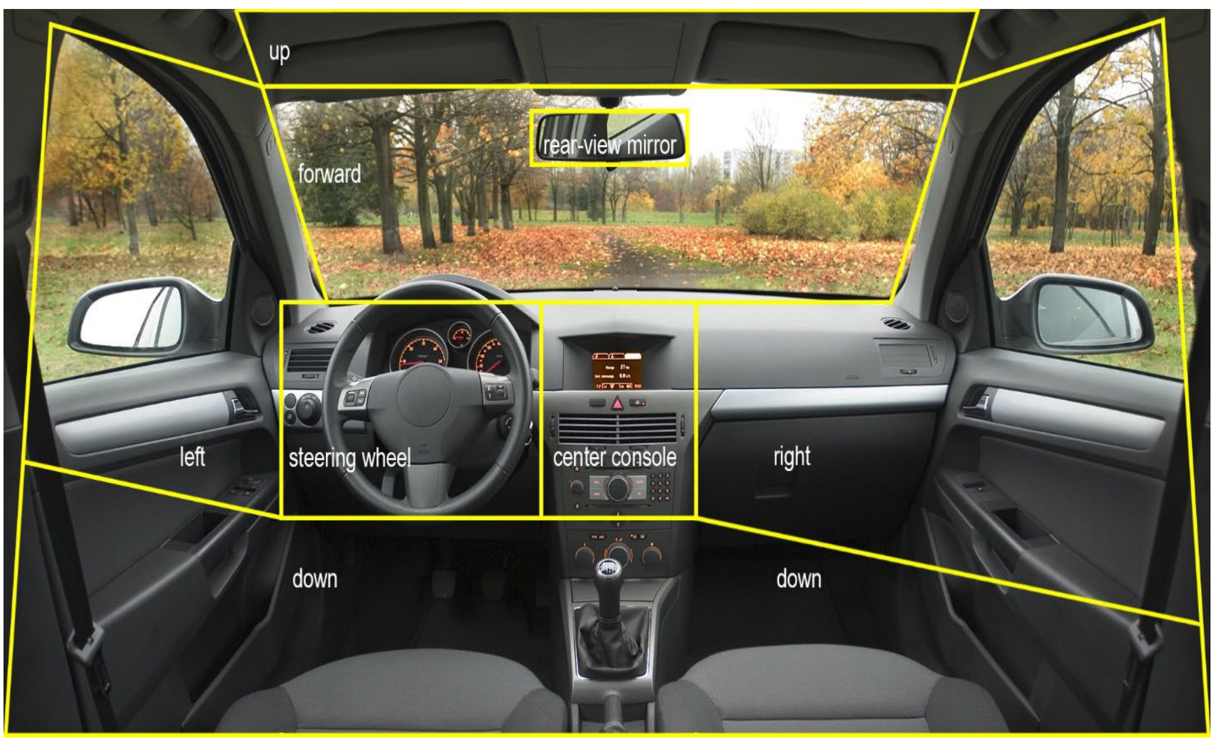
Driver characteristics, including age, gender, and other socioeconomic characteristics, were provided by VTTI along with the time series traces. Driver distraction and kinematic driver characteristics were initially reduced for 115 time series traces. It was later decided that having VTTI reduce additional data was more time and cost efficient. Due to the cost of reducing driver face video, only 984 additional traces were reduced for a total of 1,099.

Characteristics reduced include behaviors such as whether the driver's hands were on the steering wheel, impairments (e.g., drowsiness, intoxication), seat belt use, driving action (e.g., failure to yield), and speeding (exceeding the speed limit or driving too fast for conditions). Driver distraction was also coded in terms of secondary tasks, including non-driving-related glances away from the driving task.

Driver glance locations and any visual distractions (i.e., distractions that drew the driver's glance away from the forward roadway) were manually coded at the secure enclave at VTTI. These behaviors were coded from 2 miles upstream of the start of the work zone through 1.5 miles into the work zone.

For each trace, the driver's glance locations and visual distractions were coded at 15 Hz. Possible glance locations are shown in in Figure 2.7 and included the following:

- Forward
- Left
- Right
- Up
- Down
- Over the shoulder (not shown in the figure, but involved a glance beyond the B pillar)
- Center console
- Steering wheel
- Rear view mirror
- Other (used when blinks, squints, or closed eyes lasted more than 10 frames)
- Missing (used when the eyes were obscured or obstructed for more than 10 frames or when video was missing)



Original vehicle interior (before markup and annotations) from Shutterstock

Figure 2.7. Glance locations

Distractions were only coded when they were associated with a glance away from the forward view. For instance, if a driver was looking forward but talking to a passenger, that was not coded as a distraction.

However, if the driver looked to the right at the passenger while talking to him/her, that was coded as a distraction. Distractions were coded as follows:

- Passenger
- Route planning (locating, viewing, or operating a device)
- Moving or dropped object in vehicle
- Animal/insect in vehicle
- Cell phone (locating, viewing, or operating the device)
- IPod/MP3 player (locating, viewing, or operating the device)
- In-vehicle controls
- Drinking/eating
- Smoking
- Personal hygiene
- Other task

In addition, because the use of cell phones in work zones was a research question of particular interest to the research team and TAC, the use of a cell phone was coded in its own category in addition to being coded as a visual distraction. VTTI coded the respective timestamps for the beginning and end of a cell phone conversation. If the beginning or end occurred outside of the time frame requested for the time series trace, the beginning or end timestamp of the coding period was used to indicate the respective beginning or end of the cell phone conversation. Distractions caused by a cell phone that were not associated with a glance away from the forward roadway were also included. These included tasks such as reaching for the phone, adjusting the charger, texting, etc. Hands-free usage was not able to be determined because cell phone records were not available for all traces.

2.3.5 Quality Control/Quality Assurance of the Reduced Data

Because the data were reduced by multiple researchers over a period of time, there were inconsistencies and irregularities in the coding. Efforts were made to minimize these human errors in the traces that were ultimately used in the analyses. Three hundred forty-three coded time series traces (0.1 seconds apart) from work zones on four-lane divided roadways were stacked together, and the data set represented a combined file comprised of multiple time series files that included other variables associated with the time stamps. Similarly, 511 traces from work zones on multi-lane roadways were stacked together. Driver characteristics (e.g., age and gender) provided for each driver by the VTTI team were linked to these data sets. Mismatches between the variables of different traces were identified, and efforts were made to minimize errors. For example, the roadway's median type was coded in some traces upstream of the work zone, in some for the entire trace, and in some for a certain portion of the trace. For other variables, such as work zone configuration, channelizing device, and weather/lighting conditions, different coders used different subcategory names.

Some traces from each of the two data sets were spot-checked against the available forward videos. Missing information for certain variables in the data sets were imputed using available information from traces from the same work zones.

2.4 2.4 DEFINING LEGIBILITY DISTANCE

Sign and object legibility distance was used to determine the point upstream from a sign at which the sign impacts driver behavior. It was assumed that drivers could begin reacting to the presence of a sign or object as soon as it could be detected and interpreted. As a result, sign legibility distance was used to determine the influence area for each sign.

Sign legibility distance depends on the time it takes for a driver to read the sign and then react and maneuver to comply with the sign. As the vehicle's speed increases, the viewing distance decreases, which means that drivers need more distance to view the entire message. In addition, legibility depends on the sign's placement (perpendicular or parallel). Overall, legibility distance is a complex phenomenon that describes the amount of time drivers need to detect a sign, read it, and then react to the displayed message based on the surrounding traffic scenario (Bertucci 2006). Legibility distance differs by the type of work zone sign and the speed of the surrounding traffic. Other factors affecting legibility distance are the driver's perception time, the driver's reaction time, time of a day, the driver's acuity of vision, and the driver's age.

The legibility distance for each type of work zone sign was calculated to determine how far upstream a sign would have be visible to the average driver for it to influence driver behavior. This was referred to as the distance of influence for each sign. The legibility distances for various types of signs or objects were determined based on the MUTCD, findings from various studies, and engineering judgement.

A minimum legibility index ratio of 30 feet of legibility distance per inch of letter height was used in accordance with the MUTCD. For example, a letter height of 6 inches would yield a minimum legibility distance of 180 ft for static work zone signs. The rationale for selecting the legibility distance for each sign type is described below. Table 2.6 summaries the legibility distances used for the different types of work zone signs in this study.

Table 2.6. Legibility distance for different types of work zone signs

Type of Work Zone Sign	Legibility Distance, ft (m)
Static Work Zone Sign with 6 in. Letter Height	180 (54.86)
CMS	600 (182.88)
Arrowhead VMS or CMS	600 (182.88)
Speed Limit Signs (Normal, Work Zone, Feedback)	450 (137.16)
Lane Ends Sign	450 (137.16)

2.4.1 Static Work Zone Signs

Using MUTCD guidance, a legibility index of 30 feet of legibility distance per inch of letter height was used, with an assumed letter height of 6 inches, which yields a legibility distance of 180 feet for this sign type.

2.4.2 CMS

CMS is used to refer to both changeable message signs and dynamic message signs. General guidance on displaying messages on a DMS or CMS indicates that on roadways with speed limits of 55 mph or higher, signs should be visible from half a mile under both daytime and nighttime conditions. The message should be designed to be legible from a minimum distance of 600 feet for nighttime conditions and 800 feet for normal daylight conditions. The MUTCD similarly recommends that changeable message signs should be legible from at least 600 feet for nighttime conditions and 800 feet for normal daylight conditions.

Since the guidance consulted for this study agrees that the message displayed on a CMS should be legible from at least 600 feet, that was the distance utilized in the analyses.

2.4.3 Arrow Boards

The legibility distance for arrow board signs was selected to be the same as that for a CMS (600 feet). In reality, an arrow board can be detected at a much greater distance, but in the absence of additional information, it was decided to use the conservative estimate for a CMS.

2.4.4 Speed Limit and Dynamic Speed Feedback Signs

A study by Perez et al. (2016) showed that, depending on the type and placement of the sign, the mean legibility distance for speed limit signs is close to 1,250 feet due to the large size of speed limit numbers and universal driver recognition of this type of sign. Jacobs et al. (1975) found that the legibility distance for signs displaying symbols was double that of alphanumeric signs. Other studies have also found that increasing the character height does not linearly or proportionally increase the sign's legibility distance. For instance, doubling the character height does not double a sign's legibility distance (Allen et al. 1967). Garvey and Mace (1996) found that increases in character height greater than about 8 inches resulted in non-proportional increases in legibility distance.

Given that work zone speed limit signs vary considerably, an average character height of 15 inches was assumed for the speed limit characters, and the legibility distance was calculated as 450 feet.

2.4.5 Lane Ends Signs

The lane ends sign uses a symbol larger than the characters used on other sign types. A study by Paniati (1988) used an FHWA sign simulator to show a legibility distance equivalent to 295 feet (90 meters) for the lane merging sign (W4-1). Another study by Zwahlen et al. 1991 involving actual field tests found the legibility distance for the W4-1 sign to be close to 900 feet, which is significantly larger than the distance found by Paniati (1988). Since the two studies showed a wide range, it was assumed that the effect of the size of the symbol on a lane ends sign was comparable to that of the text size on a speed limit sign. As a result, a legibility distance of 450 feet was utilized in the present study.

CHAPTER 3: EVALUATION OF REACTION POINT

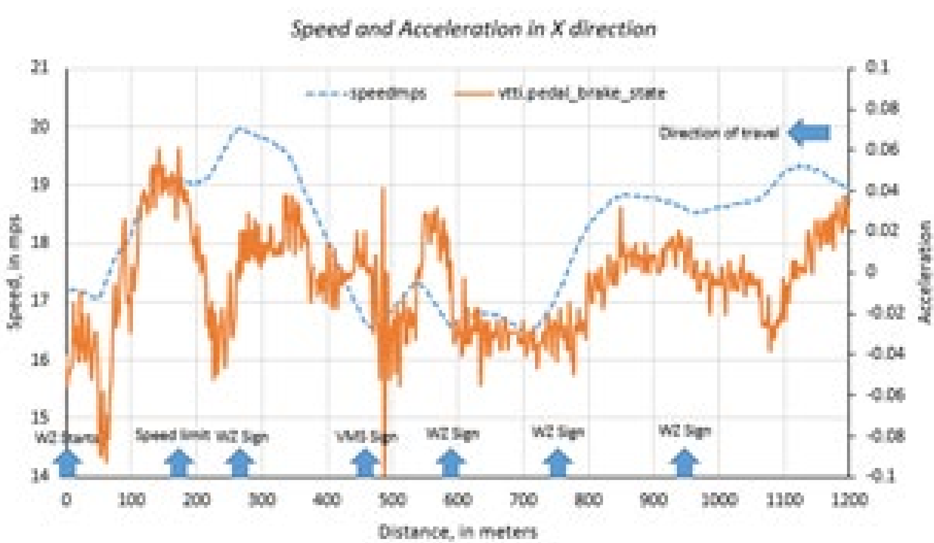
Several different analyses were conducted to assess the data from different perspectives. This chapter describes an analysis which identified where drivers began reacting to a particular traffic control device.

3.1 INTRODUCTION

The main objective of this analysis was to assess where drivers begin reacting or responding to different work zone signs in the advance warning area. Different surrogates, such as change in acceleration, speed, lane position, or pedal position, have been used to detect changes in driving behavior (Chen et al. 2015, Sayer et al. 2007, Af Wåhlberg 2008, Miyajima et al. 2006). It is assumed that when drivers are presented with traffic control or changes in roadway characteristics, they are likely to engage in some measurable response, such as adjusting their speed or attending to their lane position.

Several surrogate measures were considered based on those utilized by other researchers. Steering wheel position has been used as a measure of driver attentiveness (Kircher and Alstrom 2017; Bach et al. 2008). However, steering wheel position could only be extracted from the time series traces for a subset of vehicles due to differences in vehicle systems. As a result, this measure could not be utilized. Lane position is not an accurate reflection of driver behavior in work zones since its measurement relies on lane lines, which are often obscured, missing, or overlapping in work zones. Pedal position was not available for a large number of traces, and as a result using this measure would have resulted in a much smaller sample size. Pedal position is also correlated to speed.

Forward acceleration was also considered as a surrogate measure, but the manner in which the acceleration data were gathered resulted in a significant amount of noise, as shown in Figure 3.1.



Data source: VTTI

Figure 3.1. Vehicle kinematics showing noise in the acceleration data

Additionally, acceleration and speed are highly correlated. Since the speed data had less noise, was more likely to be reported at regular intervals in the data, and was a common measure used in the literature, speed was selected as the variable of interest to detect changes in driving behavior.

A change in speed was used as a surrogate for driver reaction. It was assumed that when drivers encounter a work zone feature, such as traffic control or equipment, they will decrease their speed. However, in some cases drivers do not decrease their speed when they encounter a work zone feature. They may have already slowed to a safe speed at the start of the work zone and as a result do not need to take further action. Additionally, a driver may see a work zone feature and become more alert and prepared to take action when needed but does not slow down. In many cases, drivers may simply not change their speed even when conditions indicate that they should.

3.2 DATA

This study focused only on work zones for 4-lane divided roadways. Only traces with good speed data (less than 10% missing speed data) within the advance warning area were used. Additionally, only traces which could be considered as "freeflow" were utilized. This resulted in 299 time series traces corresponding to 142 unique drivers and 25 unique work zones on 4-lane divided roadway with either lane or shoulder closures as shown in Table 3.1. All signs included in the advance warning area were included in the analyses.

Table 3.1. Summary of traces used in the response model

Type of Work Zone	Unique Work Zones	Total number of traces	Unique Drivers	States
All	25	299	142	(PA = 140 and NY = 159)
Shoulder Closed	8	82	56	
Lane Closed	19	217	107	

3.3 MODEL DESCRIPTION FOR EVALUATION OF REACTION POINT

Several methods are available to detect response point locations based on change in mean or variance or change in parameters of the fitted linear segments (Fryzlewicz 2014). Based on the nature of the data set, a piecewise linear regression approach was used to detect response points. Models were developed in R using "Segmented" package. A linear model was developed for each time series using speed as a dependent variable. Data were modeled for a distance of 200 feet upstream of the first work zone sign to the start of the first taper. Depending on the placement of the first sign, the length of the upstream section differed by work zone. The model used for this package is as follows in Eq. (3-1).

$$Y=\beta_{0}+\beta_{1} D+\beta_{2} (D-D^{*}) \qquad (3\text{-}1)$$

where, Y is the dependent variable for each model, β_{0} is the constant, β_{1} is the left slope, β_{2} is the difference in slopes, D is distance upstream from beginning of work zone (negative value); and D^{*} is response point (the distance at which the driver shows response).

The model detects response points if there is a significant difference in the slope of the fitted model (Muggeo 2008). Thresholds can be set so that only changes of a certain magnitude are found. This is important since there is a certain amount of noise in the data and not all significant changes in speed necessarily indicate a driver is reacting.

Since numerous minor changes in speed were present in the time series traces, a threshold for what was indicative of a change in driver behavior was established. Several researchers have used a speed reduction of 2 to 7 miles per hour (mph) as a threshold to detect response to work zone signs (Benekohal et al. 2010; Edara et al. 2013; Finley 2008; Finley et al. 2014; Sorrel et al. 2007). However, the scientific rationale for this range of thresholds was not explained in the available literature. To assess an obvious point at which the number of response points dropped off rapidly thus indicating a threshold between regular driving and actual speed reductions due to external stimuli, a sample analysis was done using 51 time series traces from 39 unique drivers across 8 different work zones and response points were detected in each trace.

Figure 3-2 shows the distribution of number of response points with reduction in the speed with a range from 2 to 10 mph both within the advance warning area (with an average distance of half mile) and half mile upstream of it. Only 75% of traces showed at least one response point in the advance warning area while only 35% showed at least one response point in the upstream area. Comparing the number of response points in each area separately, it shows large number of response points associated with a threshold of ≥ 2 mph both in advance warning area and similar in the upstream area which shows reduction in speed as a part of the normal driving in the absence of external stimuli. Again, it shows number of response points dropped off rapidly after ≥ 3 mph in both area that indicates the effect of external stimuli. Thus, the study assumed all the response points with speed reduction of < 3 mph as a part of the normal driving or noise in the data set. In addition, researchers studied the effect of threshold of ≥ 4 and ≥ 5 mph to check if there is any significant difference in the result.

The speed change threshold was also coupled with a deceleration rate of a certain magnitude. Otherwise, reduction in speed over a long distance would have been included. Based on past studies on driver deceleration behavior, the normal deceleration ranged from 0.17 to 0.49g (Paolo and Sar 2012). A final threshold of ≥ 3 mph (1.34 meter per second) within a deceleration rate in the range of 0.01 to 0.2g (1g = 9.81 m/s2) was considered as a threshold for further analysis. The response points due to lane merge, traffic entering from ramp, and sudden braking due to traffic ahead were removed. The effect of roadway geometry was not considered since the grade was reasonably flat in most cases and no sharp horizontal curves were present.

3.4 CHANGE POINT MODEL

The change point model was run for each of the 299 time series traces and response points identified for the advance warning area. Statistically significant change or response points were detected for each trace using the speed and acceleration threshold described in the previous section.

A total of 407 response points was identified from 253 traces (see Figure 3.2).

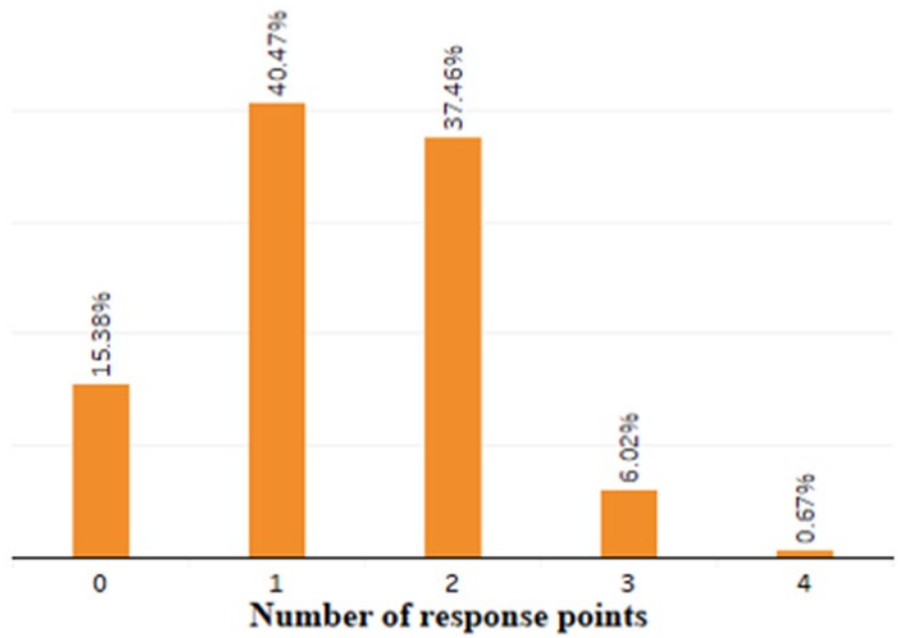


Figure 3.2. Percentage of time series traces (Event IDs) with associated number of response points

Of the 299 traces, 46 time series traces (15%) had no discernable response points. The majority of drivers had one or two response points in the advance warning area. This suggests most drivers reacted several times as they approached the work zone.

Only 67% of the response points were correlated to a known feature in the work zone. The remaining were not correlated to a feature and were not included in the model.

The locations of response points were spatially mapped to work zone signs to determine the number of response points within the legibility distances and downstream buffer for all signs.

Table 3.2 below shows the average location of response points for each type of sign.

Table 3.2. Average location of response points by type of sign

Signs	Location	Proportion of response points, %	Average distance of response point, meters	Standard Deviation, meters
First Sign	Before / After	61.53 / 38.47	56.44 / 30.41	54.93 / 21.09
CMS	Before / After	86.84 / 13.16	113.91 / 33.78	52.81 / 30.53
Speed Limit	Before / After	78.37 / 21.63	85.31 / 23.96	49.35 / 17.13
Static Work Zone	Before / After	67.61 / 32.39	57.04 / 31.91	49.86 / 21.25
Lane Ends	Before / After	58.33 / 41.67	70.15 / 32.8	42.41 / 17.14
Enforcement	Before / After	100	87.39	54.77

As noted, for the "First Sign", 62% of drivers showed a response before the sign and responded on average 56 meters before the sign. The remaining 38% of drivers who showed a response at the first sign did so after passing the sign. The category "static work zone sign" included static work zone signs except speed limit, lane merge/closure, enforcement, or speed limit signs. When drivers encounter static work zone signs, 68% of those who showed a reaction did so upstream of the sign within 57 meters of the sign. When a "Lane End" sign was present, 58% of drivers who showed a response did so upstream of the sign and within 70 meters. As a result, around two-thirds of drivers who reacted to typical work zone signs reacted before the sign. In contrast, 78% of drivers who reacted to work zone speed limit signs did so upstream of the sign and 100% of drivers who reacted to a work zone speed enforcement sign did so upstream. They also reacted much sooner 78 meters and 87 meters upstream. This may suggest that drivers took the signs more seriously than other static work zone signs. Finally, 87% of drivers who reacted to CMS did so upstream at an average distance of 114 meter. This is likely due to the fact that CMS are visible for a much longer distance than static signs.

3.5 DEVELOPMENT OF THE RESPONSE MODEL

3.5.1 Methodology to Combine Work Zone Sign Information and Response Points

To develop the model, a buffer distance (as described in the previous section) was set to the legibility distance of each sign to precisely assess the effect of signs. The legibility distance of each sign was determined and represented the likely distance where a driver was able to see the sign and therefore react to the sign. Based on MUTCD requirements and the information about sign legibility from the literature review, legibility distance was selected for each sign type as shown in the following Table 3.3.

Table 3.3. Legibility distance for different work zone signs, in feet (meters)

Type of Work Zone Sign	Legibility Distance, ft (m)
Static Work Zone Sign with 5 in. letter height	180 (54.86)
CMS Signs	600 (182.88)
Arrowhead CMS	600 (182.88)
Speed Limit Signs (Normal, Work Zone, Feedback)	450 (137.16)
Lane Ends	450 (137.16)

Using sign location and legibility distance, an influence area for each sign was specified for each time series trace. It was assumed that a driver may react at any point after the sign was legible and may react some distance downstream. Initially a buffer distance of 80 meters downstream was utilized based on perception reaction time. However as noted in Table 3.2, all drivers responded within 50 meters downstream of a particular sign. As result, a downstream buffer of 50 meter was used. Thus, the influence area of each sign as legibility distance (discussed in Table 3.2) of that sign upstream from sign location plus 50 meters downstream.

Each response point was linked to the nearest corresponding work zone sign using the influence area for each sign. In some cases, the influence areas of two signs overlapped. In these cases, a separate node was created within the overlap area and when a response point fell within the overlapping area, it was assigned to the overlap area rather than an individual sign. Figure 3-3 shows the detailed methodology of connecting signs and response points to create a separate binary variable.

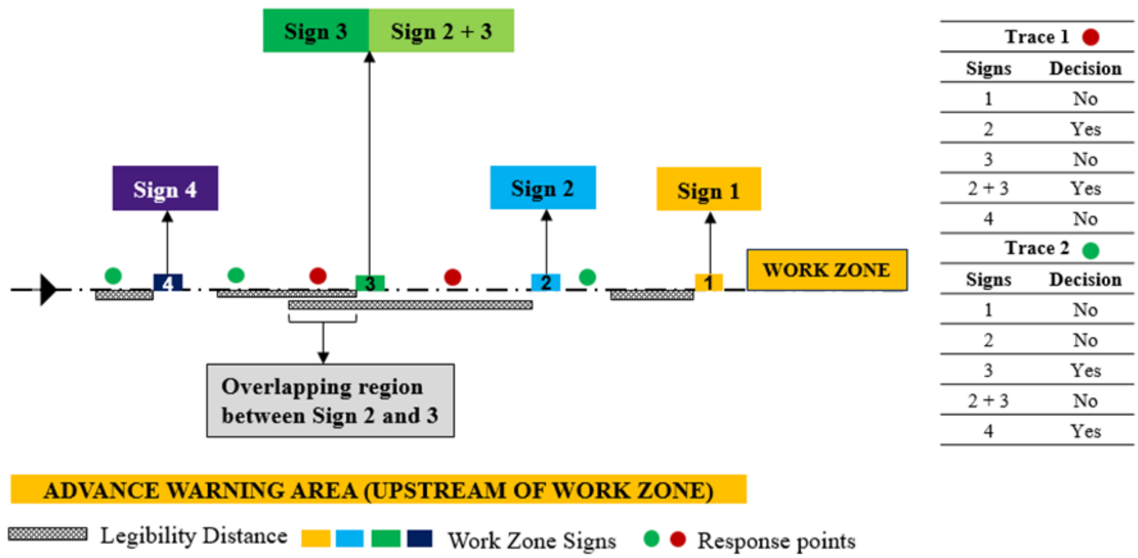


Figure 3.3. Methodology to combine work zone signs and response points

Based on the binary variable, a mixed effect logistic regression model was developed. The model included one observation for each work zone feature (node) for each time series trace. If a response point was detected within the legibility distance defined for that feature, it was recorded as 1. If no response point was detected, it was recorded as 0.

3.6 DATA FOR THE MODEL

Response points were identified for 299 time series traces corresponding to 142 unique drivers and 25 unique work zones on 4-lane divided roadway with either lane or shoulder closures. As noted in the previous sections, 46 time series traces had no discernable response points and were not included in the model. Table 3.4 shows a summary of the variables included. A node (y) was included for each sign for each trace. If a response within the buffer distance was noted, y = 1. If no response was noted, y = 0).

Table 3.4. Summary of data utilized in model

Variable	Count		
Total number of nodes (Y variable)	1529 (1 = 272, 0 = 1257)		
Total response points captured	≥ 3 mph : 272 (67% of 407), ≥ 4 mph : 225 (55% of 407), ≥ 5 mph : 186 (46% of 407)		
Work Zone (WZ) Type	**Count (Unique Traces)**	**Unique Driver ID**	**Unique WZ ID**
Total	299	142	25
Shoulder closed	82	56	8
• Right side closed	13	10	1
• Left side closed	69	50	10
Lane closed	217	107	19
• Right side closed	131	81	11
• Left side closed	86	53	9

	Different Sign types	Count (# of nodes)	Average distance to signs, meters			
	Total number of nodes	**1529**	**Min.**	**Max.**	**Std. Error**	**Average (Figure 1)**
Work Zone Signs	Static Work Zone Sign	413	57.96	2201.56	495.64	764.99
	First Sign	270	9.45	4106.16	807.07	1569.42
	• Enforcement	18	1687.74	2626.56	445.79	2164.51
	• CMS (FSTypeCMS)	22	1287.74	1753.43	134.17	1567.10
	• Static Work Zone Sign (FSTypeWZ)	230	9.45	4106.16	847.78	1523.06
	Speed Limit	310	7.11	4558.64	707.02	810.67
	• Normal (SpeedTypeNormal)	47	148.98	4558.64	689.73	1064.77
	• Work Zone (SpeedTypeWorkZone)	197	7.11	2697.36	799.11	827.86
	• Feedback (SpeedTypeFeedback)	66	110.65	670.22	108.67	578.44
	CMS	120	164.42	1922.27	585.93	1155.12
	• Trailer	123	291.88	1922.27	546.38	1228.76
	• Overhead	19	164.42	1915.32	647.28	763.69
	Emergency Sign	28	357.14	2510.60	347.32	1179.86
	Overlapping Signs	208	74.73	4394.82	546.66	749.18
	Lane Ends	180	136.03	593.55	103.04	307.29
	Number of signs at each work zone		1	10	2.17	5.71
	Number of signs passed		0	9	2.32	2.06
	Distance, meters, DSM	1529	7.11	4558.64	699.53	898.03
	Traveling speed					
	Speed difference at First Sign, mph (Traveling – Posted Speed limit)	299	-10.84	33.63	8.36	11.71
	Speed difference at all the Signs (Traveling – Posted Speed limit), mph, SD	299	-16.91	33.27	7.61	7.65
	Driver Information	**Count**	**Min.**	**Max.**	**Std. Error**	**Average**
	Driver Age (Time of trip collection)	142	17	88	19.35	48.29
	Driving experience	142	0	70	19.41	31.02
	Sex (Male = 1, Female = 0)	70				
	Number of violations	0	1	2 or more		
		226	43	30		
	Number of crashes	218	72	9		
	Other Variables / Count					
	Types of Vehicle (Car = 1)	206 / Car	20 / Pickup Truck	64 / SUV	9 / Van	
	Day vs Night (Day = 1)	242				
	Pavement Condition (Dry = 1)	273				
	Location of vehicle (Right = 1)	993				
	Distracted = 1	130				
	Normal glances = 1	1493				

3.6.1 Final Model

A mixed effect logistic regression model was used to assess the likelihood that a driver would respond to a particular work zone feature. Response points were identified for each time series trace as described in the previous section. Driver ID and work zone ID were used as random effect in this model to account for multiple samples from the same driver or work zone. A "glmer" function available in package "lme4" was used in R 3.5.1 to fit the model. The best fit model was selected based on the minimized Akaike Information Criterion (AIC). Correlations between the variables were checked prior to model development. Interaction between variables were considered in the model and their significance was checked. In addition, fitting of the model was also checked by visualizing residuals in R. Table 3.5 shows results from the final model.

Table 3.5. Final model showing different factors affecting response point

Description of the variables	Variables	Estimate	Standard Error	p-value	Odds Ratio
	(Intercept)	-0.940	0.624	0.132	0.391
Work Zone Signs+	Enforcement (EN)	-1.043	1.035	0.314	0.353
	First Sign (FS)	0.361	0.255	0.156	1.435
	Lane Ends (LE)	0.496	0.250	0.047*	1.643
	Speed Limit (SL)	-1.289	0.582	0.027*	0.276
	Changeable Message Sign (CMS)	0.882	0.328	0.007*	2.415
	Overlapping (OV)	-0.194	0.260	0.456	0.824
Interaction of Sign Types	CMS:CMS_NotActive	0.373	0.459	0.416	1.452
	SL:SpeedTypeWorkZone	1.798	0.550	0.001*	6.037
	SL:SpeedTypeFeedback	1.623	0.606	0.007*	5.068
Effect if location of signs	Distance of signs, every 100 m	-0.034	0.015	0.027*	0.967
	SL:DSM100	0.052	0.024	0.035*	1.053
Effect of speed difference	SD in mph	0.054	0.011	0.000*	1.056
Other factors	Location Right (Right = 1, Left = 0)	-0.026	0.152	0.865	0.975
	Type of WZ (Lane Closure = 1, Shoulder Closure = 0)	-1.001	0.228	0.000*	0.367
	Day (Day = 1, Night = 0)	-0.031	0.191	0.869	0.969
	Years of driving less than 5	0.156	0.158	0.324	1.169
	Gender (Male = 1, Female = 0)	-0.239	0.141	0.089	0.787
Distraction and Glance	Distracted = 1	-0.579	0.298	0.052	0.560
	Normal Glance = 1	-0.179	0.499	0.720	0.836

* Significant at 5% level of significance, AIC = 1381.40, Log-likelihood = -668.70
+ Baseline: Static Work Zone Sign

No statistically significant response was noted for the first sign encountered by drivers as they entered the advance work area. When a driver encountered a "Lane Ends" sign the odds of showing a response was 1.64, which was expected since a driver may need to take some action such as merge.

Drivers were 6.04 times more likely to respond when a work zone speed limit sign was present and were 5.07 times more likely to respond when the speed limit sign included a dynamic speed feedback sign than for a regular static work zone sign. Drivers were 2.42 times more likely to react when an active CMS was present compared to a regular static work zone sign. When the CMS was inactive, drivers were 1.45 times more likely to react, but the difference was not statistically significant.

In general, the farther a driver was from the start of the work zone, the less likely they were to show a response. For each 100 meters farther away they were, a driver was 0.97 times less likely to respond. However, the opposite effect was noted, the farther a speed limit sign was placed from the start of work zone, the more likely a driver was to respond (OR = 1.05 with every 100 meters increase in distance). When a “Lane Ends” sign was present drivers were 1.64 times more likely to respond than for a static work zone sign.

Drivers who were traveling over the speed limit were more likely to show a response than drivers traveling at or below the speed limit. The odds of a driver showing response increased by 1.06 times with every one mile per hour increase in driving speed over the posted speed limit. This makes sense as drivers who were traveling at or near the speed limit did not necessarily need to respond.

Similarly, other variables like location of travelling lane, gender, experience, and time of a day were not found to have significant effect. Finally, result showed that distracted drivers were less likely to show response to signs in general with an odds of 0.56, although the result was not statistically significant. The lack of statistical significance is likely due to the lower sample size for distractions.

3.7 DISCUSSION

The main purpose of the analysis described in this chapter was to analyze whether drivers showed a response to certain work zone features. A methodology to detect speed response points, termed as response point was used. Several prior research studies were conducted on the compliance of work zone speed limit signs and selection of suitable posted speed limit (Finley et al. 2008). Some studies have found slight reduction in the average speed due to the posted limit signs (Banerjee et al. 2019; Finley et al. 2008; Finley et al. 2014) though the statistical significance of the reduction and the operating speed limit varies by studies. Results from this study also indicated drivers more likely to response to posted work zone speed limit than a regular static work zone sign. With finding similar to Carlson et al. 2000, dynamic speed feedback sign showed the most significant effect. Activated CMS sign was found to be significantly effective which is consistent to the finding from Thompson 2002. Prior studies concluded the speed reduction at work zones with the lane closure scenario (Carlson et al. 2000; Finley et al. 2014). As Lane Ends sign were placed closer to the merge location, this study also found a significant effect of this sign. The farther a driver is from the start of the work zone they are slightly less likely to show a response. However, the opposite effect was noted for speed limit signs. The result from speed limit signs was similar to finding from Strawderman et al. 2012 where the study found compliance with the speed reduction signs placed farther away from the work zone. In addition, speeding drivers were more likely to show a response.

CHAPTER 4: EVALUATION OF CHANGE IN SPEED

The second analysis conducted for this project evaluated how drivers changed their speed when they encountered a traffic control device.

4.1 BACKGROUND

A number of countermeasures have been utilized by agencies to get driver's attention and reduce speeds in work zones. However, there is limited information about which countermeasures are the most effective since driver behavior in work zones is not well understood.

This analysis utilized data as described in Chapter 2 to evaluate the impact of traffic control devices in reducing driver speed in work zones. Time series data were used to assess change in speed for 380 drivers over 104 unique work zones on 4-lane or multi-lane roadways. Change is speed was the measured as the difference between speed for an individual time series trace from a point upstream of a particular TCD (i.e., sign, CMS) to a point just downstream of the TCD. Speed upstream was at a point before the TCD should have been visible to the driver. Change in speed was measured for any type of TCD encountered in the work zones evaluated. Several of the TCDs are not typically used for speed reduction per se. However, reduction in speed also suggests a driver noticed and reacted to an individual TCD. Change in speed was estimated using a linear mixed-effect (LME) model.

4.2 DATA REDUCTION

The objective of the work discussed in this chapter was to assess the impact of traffic control devices on speed. Information such as presence of regular speed limit signs was available in the RID for some roadways. However, the RID did not contain any specific information about work zones. As a result, traffic control devices were identified using the forward roadway video and included static work zone signs (i.e., advisory, enforcement, speed limit), changeable message signs (CMS), dynamic speed feedback signs (DSFS), normal speed limit signs, and arrow boards. CMS included trailer mounted which were typically placed for the work zone as well as overhead CMS which were a permanent feature of the roadway and could display a variety of messages such as "Message Monday", congestion alerts, or work zone information. Overhead message signs were noted as actively displaying a message (Active) or blank (Not Active). Trailer mounted CMS and DSFS were initially noted as being active or not active but due to sun glare, vehicle position relative to the sign, and video quality status, could not consistently be identified. As a result, differentiation between active and not active was not included for trailer mounted CMS and DSFS.

Number of lanes and type of median upstream of the work zone were also recorded. Other work zone features such as type of closures (shoulder, lane), start of merge, end of work zone, type and location of barriers used within work zone (i.e., concrete, cone), presence of glare screens, presence of equipment or workers, number of closed lanes, and lane shifts were also recorded.

Data were coded for a distance approximately 2 miles upstream of the start of wok zone and 1.5 miles downstream of this point. All the work zones included in the analysis had a lane and/or shoulder closure. The point of closure was used as the work zone start point.

Each characteristic was coded with the corresponding timestamps for each trace. As a result, location of each characteristic (i.e., TCD, start of work zone) could be related to vehicle position. The legibility distances for each traffic control device was determined in order to identify the influence area for each sign. Legibility distance was determined using a legibility index of 30 feet per inch of letter height. This was also compared with the Manual on Uniform Traffic Control Devices. The following legibility distances were used:

- Speed limit: 450 ft based on height of speed limit letters
- DSFS, CMS, Arrow board: 600 feet based on MUTCD nighttime standard for CMS
- Static signs with regular text: 180 feet based on MUTCD

Each TCD was treated as an individual datapoint. Speed was extracted around 50 meters (164 feet) upstream of the legibility distance for each TCD (i.e., 450 + 164 feet for speed limit signs). Speed at this point represented, a driver's speed choice before encountering the TCD. Speed was also extracted 50 meters downstream of each TCD. This represented driver's speed choice after encountering the TCD. The 50-meter distance downstream was selected to account for drivers who slow after passing the sign. Change in speed was the difference between the upstream and downstream speeds. Other metrics such as maximum change in speed were considered but were not reasonably different than the metric selected.

The number of TCD a driver encountered within the legibility distance of a particular TCD was also calculated since it was felt that being presented with multiple signing may lessen or increase the impact. This variable was also included in initial models.

Viable events were provided to VTTI and their analysts coded glance location and distraction as noted in Section 2.3.4. Glance location was coded as locations where a driver was attending to the roadway task (i.e., forward, rear view mirror) or not attending to the roadway task (i.e., down, back, passenger). Distractions, such as eating, drinking, texting, were coded when they were associated with a glance away from the roadway task. The distraction category included any cell phone related activities where the driver was looking away from the roadway tasks. Cell phone use was also coded as an independent variable and included all cell phone use (when identifiable) and did not need to be associated with a glance away from the driving task. Cell phone use included dialing, talking, texting, or handling a cell phone. Distraction, glance data, and cell phone were joined to the corresponding time series trace using time stamps.

A total of 775 time series traces were reduced for use in the model. This included 380 drivers over 104 different work zones.

4.3 METHODOLOGY

Change in speed for each TCD was the dependent variable and was modeled using a linear mixed-effect (LME) model. An LME model consists of two additive components: the fixed effects and the random effects. Change in speed at each traffic control device was an independent observation. This resulted in 3,949 observations. Traffic control devices include the following (number of observations for each is also shown).

- Arrow board = 231
- CMS= 186
- DSFS = 39
- Enforcement = 81
- Lane Merge = 377
- Other work zone sign = 2066
- Overhead CMS = 143
- Regular speed limit = 191
- Work zone speed limit = 635

The category of "Other" include all other static work zone-related signs not explicitly mentioned. Overhead CMS were further differentiated by active or not active. This differentiation was not provided for trailer mounted CMS and DSFS since in some cases it was not possible to determine from the video whether the board was active. All other static work zone-related signs not explicitly mentioned were placed under "other work zone signs." Examples include "Lane Ends", "Road Work Ahead," "Right/Left Lane Closed Ahead", etc.

The fixed effects covariance structure in the LME considers the possible variability introduced by grouping variables (work zone, driver, and event). Roadway type (i.e., 4-lane versus multi-lane) was the first variable considered. However initial results for both roadway types were similar and as a result data were combined for the models. Other variables such as age and gender were examined but did not show a pattern and were not included.

The following variables were considered in the models.

- **Distance (in meters):** The distance from the sign to the work zone start was included. Only signs 2000 m upstream and 2000 m downstream were considered for this analysis. The values in the upstream area are expressed as negative numbers.
- **Density:** This includes the number of TCD within the legibility distance for each TCD not including the TCD itself.
- **Work zone configuration:** This includes left lane and right shoulder closed, left lane closed, any shoulder closed (right or left shoulder), and right lane closed.
- **Median and barrier:** This variable captures whether type of median upstream and type of barrier within the work zone. Initial analyses suggested median types other than concrete were similar (i.e., grass, painted) so median was categorized as concrete barrier or "Other Median." Other analyses

had shown driver behavior was similar for work zone barriers other than concrete (i.e., panel, barrel) and as a result barrier was aggregated to concrete barrier or “Other Barrier”.

- **Environmental:** This included time of day (day or night) and whether it was raining or dry. Events with adverse weather (snow, ice, heavy downpour) were rare and were not included.
- **Cellphone use:** This variable indicates whether a driver was engaged in a cell phone task within the legibility distance plus the 50 meters upstream and 50 meters downstream which was used to calculate change in speed.
- **Glances away over 1 second:** This variable indicates whether the driver engaged in one or more glances away from the driving task for one or more seconds within the legibility distance plus the 50 meters upstream and 50 meters downstream.

Table 4.1 shows a summary of the number of observations for each.

Table 4.1. Summary of variables

Variable	Count
Density	No additional signs within legibility distance = 2802 1 or more signs within the legibility distance = 1147
Work zone configuration	Left lane and right shoulder closed = 533 Left lane closed = 1620 Shoulder closed (left or right) = 1052 Right lane closed = 744
Road type	4-lane = 1795 Multi-lane = 2154
Median and barrier	Concrete median upstream with concrete barrier in work zone = 1352 Concrete median upstream with other barrier in work zone = 962 Other median upstream and concrete barrier within work zone = 859 Other median upstream and other barrier within work zone = 776
Environmental	Day/dry = 2821 Day/rainy = 282 Night/dry = 761 Night/rainy = 85
Any cellphone	no = 2879 yes = 570
Glances away over 1 s	none = 3221 1+ = 228

Change in speed in the LME is modeled as the l-th traffic sign in the i-th work zone by the j-th driver during the k-th event is modeled as

$$y_{ijkl} = x_{ijkl}^T \beta + \alpha_i + \eta_j + \nu_k + \epsilon_{ijkl},$$

where x_{ijkl}^T is the vector of covariates and β the vector of effects? The terms $\alpha_i + \eta_j + \nu_k + \epsilon_{ijkl}$ are all independent and normally distributed with mean zero and variances σ_α^2, σ_η^2, σ_ν^2 and σ_ϵ^2, respectively.

The correlation structure can be computed for any of these terms, for example, the correlation between two observations of change in speed from two different drivers on the same work zone is given by

$$cov(y_{ijkl}, y_{ij'k'l'}) = \frac{cov(\alpha_i + \eta_j + \nu_k + \epsilon_{ijkl},\ \alpha_i + \eta_{j'} + \nu_{k'} + \epsilon_{ij'k'l'})}{\sqrt{var(y_{ijkl})var(y_{ij'k'l'})}} = \frac{\sigma_\alpha^2}{\sigma_\alpha^2 + \sigma_\nu^2 + \sigma_\nu^2 + \sigma_\epsilon^2}.$$

A Bayesian implementation was used to fit the model. The regression was fit in R (version 4.0.2) with the Rpackage “brms” (version 2.13.3), which is a Bayesian approach. All the priors were non-informative. The 8000 MCMC chains were extracted and the warm-up threshold was set at 4000 samples. The convergence was check with the R value and trace plots. The model fit was checked with posterior predictives.

4.4 RESULTS

The fixed effects included in the model were type of traffic control device, distance to the beginning of the work zone, and road type. Work zone ID and trace ID were included as random effects (the random effect of the driver was negligible). Selection of the final model was based on forward stepwise selection. This included evaluating the impact of individual independent variables to determine whether they should be included in the final model. In some cases, the variable appeared to have some impact but was not determined to be statistically significant, which may be due to sample size. As an example, change in speed by cell phone use by sign type is shown in Figure 4.1.

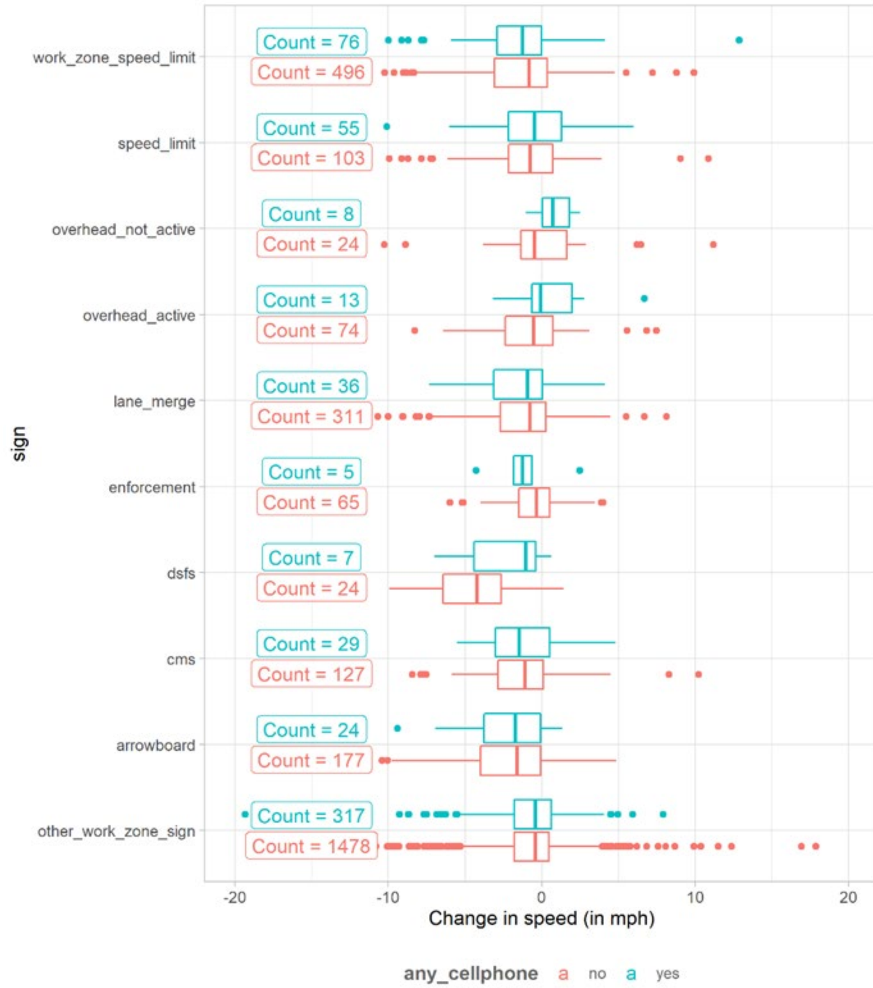


Figure 4.1. Change in speed by cell phone use for each TCD

As noted, the change in speed for many of the categories of TCD are greater for scenarios when drivers were not engaged in a cell phone task. For instance, at active overhead CMS, a speed change of slightly more than zero was noted when the driver was engaged in a cell phone task while a decrease of around 1 mph was noted when no cell phone task was noted. However only 29 drivers were engaged in a cell phone task when encountering a CMS. Similarly, a speed reduction of around 1 mph occurred for DSFS when a driver was engaged in a cell phone task while an average reduction of 4 mph occurred when no cell phone task occurred. However, only 7 drivers were engaged in cell phone tasks with a DSFS present. As a result, sample sizes were reasonably small. The impact of cell phone was not statistically significant and was not included in the final model. As noted, this is likely due to sample size.

Results for the final model are shown in Table 4.2.

Table 4.2. Random effects estimates

Effect	Estimate	Estimated Error	95% CI
Event ID	0.4132	0.0586	0.2936
Work Zone ID	0.5840	0.0743	0.4490

The models were developed using meters per second (m/s). As a result, model output is shown using this units. Results were converted to miles per hour for charts and discussion of results.

The distance of a TCD from the start of the work zone was relevant but the relationship was not linear. As a result, there was no clear pattern that indicates the whether the impact of TCD increases or decreases at the same rate closer to the work zone start. A non-linear spline function was used to model the effect of distance on change in speed. The parameters associated with speed are presented in Table 4.3 but are not easily interpreted by themselves; instead, they are interpreted through the conditional effect as shown in Figure 4.2, which shows the overall impact of distance on change in speed.

Table 4.3. Standard deviation of smoothing terms

Parameter	Estimate	Estimated Error	Upper 95% CI	Lower 95% CI
Distance parameter for work zones on 4-lane roadways	2.3862	0.9567	1.1094	4.7620
Distance parameter for work zones on multi-lane roadways	1.1253	0.8276	0.1924	3.3333

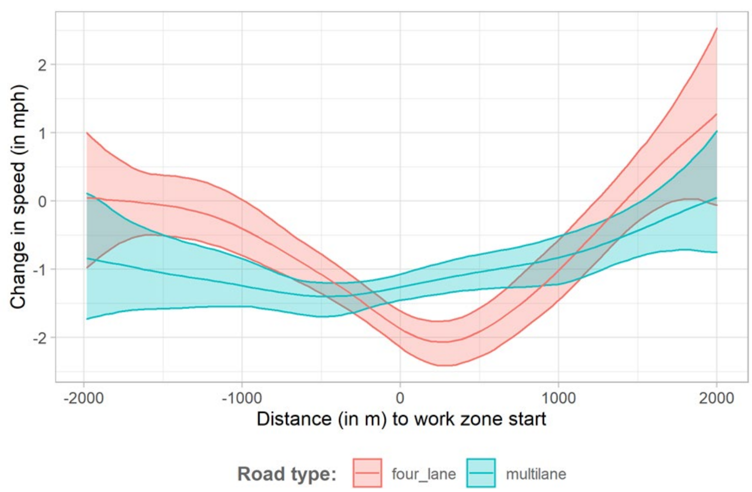


Figure 4.2. Impact of distance on change in speed for traffic control devices

As noted, speed has a different impact for work zones on 4-lane roadways as compared to multi-lane roadways. As shown, on 4-lane roadways, when drivers encounter TCD more than 1000 meters upstream, the impact is smaller. Within 1000 meters upstream to a point just after the start of work zone, drivers are much more likely to change speed for any given traffic control device the closer they are the work zone start. After this point, drivers are decreasingly less likely to slow for any given TCD. A similar but less pronounced impact is shown for work zones on multi-lane roadways. Some of the impact may be due to the type of sign located nearest the start of work zone. For instance, an arrow board is usually near the lane closure. However, no clear interaction was noted between distance and a specific type of TCD.

Table 4.4 shows fixed effects for the best fit model. The reference level is "Other Signs" which means that each result is in comparison to the change in speed for "Other Signs."

Table 4.4. Fixed effects estimates

Variable	Estimate	Estimated Error	Upper 95% CI	Lower 95% CI
Intercept	-0.4973	0.0791	-0.6504	-0.3407
Arrow board	-0.4408	0.1271	-0.6824	-0.1914
CMS	-0.1983	0.1333	-0.4617	0.0673
DSFS	-0.9861	0.2644	-1.4989	-0.4764
Enforcement	0.1659	0.1874	-0.1942	0.5367
Lane merge	-0.0539	0.1039	-0.2553	0.1560
Overhead CMS (active)	0.2854	0.1848	-0.0774	0.6451
Overhead CMS (not active)	0.5925	0.2443	0.1097	1.0677
Speed limit sign	-0.2465	0.1315	-0.5006	0.0102
Work zone speed limit sign	-0.2286	0.0885	-0.4047	-0.0585
Parameter for distance for 4-lane roads	3.1345	3.3105	-3.5784	9.6053
Parameter for distance for multilane roads	0.8808	2.0346	-3.2662	5.2395

For instance, the presence of DSFS is associated with a -0.98 m/s change in speed more than “Other Signs”. Other variables such as type of barrier present for each TCD and driver glance location and cell phone use were evaluated. However, none of these variables were statistically significant.

Figure 4.3 shows the conditional effects for static traffic control device.

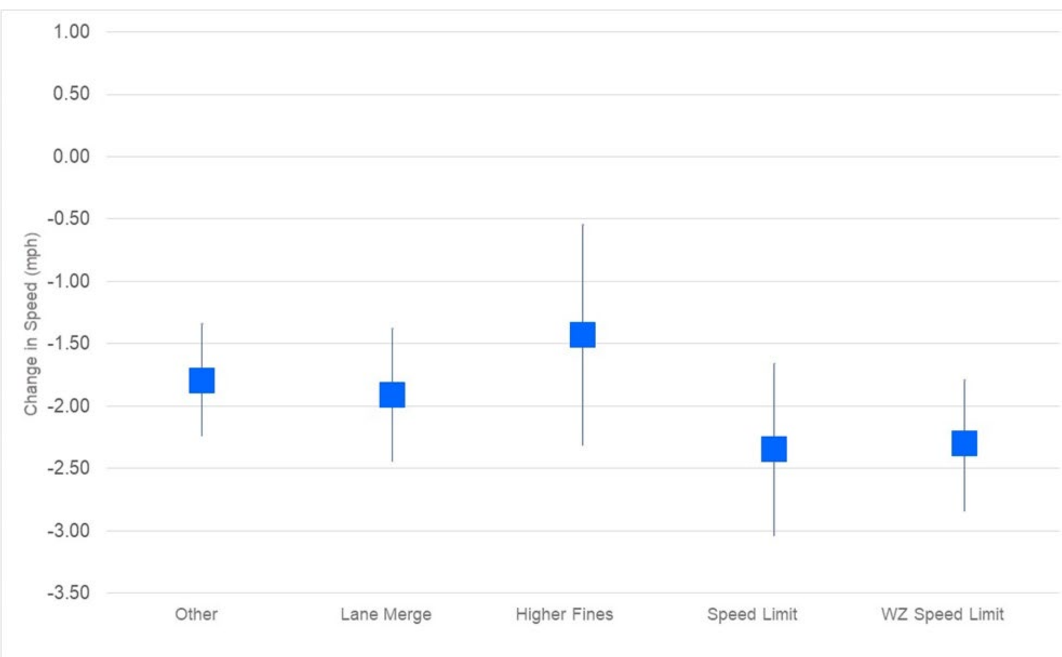


Figure 4.3. Change in speed and 95% confidence interval for static work zone traffic control devices

Figure 4.4 shows the condition effects for electronic traffic control devices.

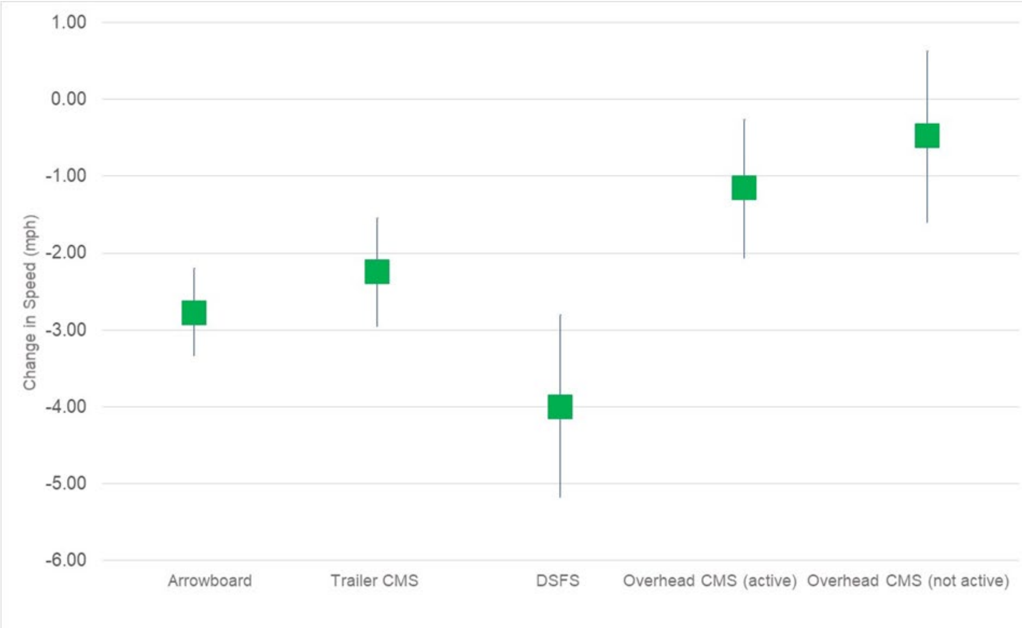


Figure 4.4. Change in speed and 95% confidence interval for electronic work zone traffic control devices

Speed was converted to miles per hour (mph) for the chart. The estimate as well as the upper and lower 95% confidence interval are shown for each TCD. Dynamic speed feedback signs were the most effective traffic control devices in terms of eliciting a change in speed with an average decrease of 4.0 mph. When drivers encountered an arrowboard, they decreased speed by 2.8 mph. Decreases of 2.2 mph were estimated for trailer mounted changeable message signs. The status of overhead changeable message signs (active versus not active) was modeled separately. Overhead message signs are not necessarily related to the work zone (i.e., Message Monday) but were included since it was felt it may have an impact on speed. When an overhead CMS was active, a reduction of 1.2 mph was noted and when not active a reduction of 0.5 mph resulted. The results for "not active" were not statistically significant but were presented for completeness since the results for active were significant.

Presence of a lane merge sign resulted in a 1.9 mph decrease in speed. A reduction of 1.4 mph was noted when a driver encountered an enforcement sign. This category included any sign which indicated penalties such as "Fines Doubled" or "Speeding Fines Increased." It should be noted, this change was due to presence of the physical sign. Evaluating the speed impacts of policies for higher fines within work zones was not within the scope of this project.

Both regular speed limit and enforcement speed limit sign resulted in a 2.3 mph decrease in speeds. The category of "Other" covers any other static work zone sign not included in the categories discussed above. This would include signs such as "Work Zone Ahead", "Work Zone Ends", "Lane Shift", "Shoulder Work," etc.

4.5 SUMMARY AND DISCUSSION

Data from the second Strategic Highway Research Program (SHRP2) was used to evaluate the impact of traffic control devices in reducing driver speed in work zones. Time series data were used to assess change in speed for 380 drivers over 104 unique work zones on 4-lane or multi-lane roadways. Change in speed was estimated using a linear mixed-effect (LME) model.

The final model indicated the following impact for various traffic control devices:

- **DSFS:** decreases of 4.0 mph were found and results are consistent with several other studies that evaluated DSFS in work zones and reported decreases from 2 to 10 mph (MDSHA 2005, Thompson 2002, Brewer 2005, Fontaine 2017, Carlson et al. 2000, and Meyer 2003);
- **Arrowboard:** decreased of 2.8 mph
- **Trailer mounted CMS:** decrease of 2.2 mph were noted in this study which are consistent with other studies which have found decrease from 2 to 11 mph (Thompson 2002, Sorrel et al. 2006);
- **Overhead CMS (active):** decrease of 1.2 mph
- **Lane merge:** decrease of 1.9 mph
- **"Higher Fines":** decrease of 1.4 mph
- **Regular speed limit and work zone speed limit signs:** both resulted in a 2.3 mph decrease in speeds and results are consistent with other studies which found reductions between 2.3 and 4.3 mph when drivers encountered speed limit signs in work zone (Finley et al. 2008, Benekohal and Wang 1993);
- **Other work zone signs:** a decrease of 1.8 mph

All traffic control devices were included in the model and it should be noted that many of the traffic control devices are not for speed management per se. In these cases, it was assumed that a change in speed indicated drivers noticed and reacted to the TCD. While, some sign types would not be explicitly used for speed reduction, results suggest strategic placement may have some impact on speeds.

Other variables, such as work zone configuration or type of barrier, were evaluated but were not statistically significant. Driver characteristics (i.e., age, gender, glances away from roadway task, and cell phone related tasks) were included but were not statistically significant. A comparison of speed reductions by type of TCD by cell phone use did indicate differences in behavior occurred. For instance, drivers engaged in a cell phone task only reduced speed by 1 mph when they encountered a DSFS compared to a 4-mph reduction for drivers not engaged in a cell phone task. The lack of statistical significance was likely due to sample size.

Distance of the sign from the start of work zone was also statistically significant with drivers being more likely to reduce speed as they got closer to the start of work zone. However, the impact could not be associated with a particular TCD. For instance, it was not possible to determine whether a speed limit sign was more effective when it was closer to the work zone.

CHAPTER 5: MODELING BACK-OF-QUEUE SAFETY CRITICAL EVENTS

Rear-end crashes have been noted as one of the predominant types of crashes in work zones accounting for up to 51% of work zone crashes. Rear-end crashes often occur at the back of queues or in locations where congestion is present. Aggressive behavior has been linked to rear-end crash risk in work zones including tailgating (< 2 second gap), forced merges, and speeding. Distraction and inattention have also been reported as contributing factors.

The main objective of this analysis was to evaluate back of queue safety critical events (SCE) using the SHRP2 NDS to assess contributing driver and roadway factors. Back of queue scenarios were identified through a review of safety critical events in work zones coded by the Virginia Tech Transportation Institute (crashes, near crashes, or conflicts) as well as a review of time series traces in work zones collected for a related project. This resulted in 46 safety critical events and 283 “normal” events. A mixed Mixed-Effects Logistic Regression model was developed with odds of an SCE as the response variable.

5.1 DATA

Work zone characteristics such as traffic control, type of barrier, lane merge, etc. were coded using the forward video view as noted in Section 2.3.2. As work zones information was extracted, coders also identified back of queue events using a review of the forward roadway video. A back of queue event was a scenario where the subject driver encountered a slowed, stopped, or braking lead vehicle (see Figure 5.1).

VTTI

Figure 5.1. Examples of back of queue events

Additionally, VTTI, who house the SHRP2 NDS data, had identified a set of crashes and near crashes which are available through a secure data server. Crashes and near crashes at back of queues in work zones were also identified through a review of that data.

5.2 DATA REDUCTION

Roadway characteristics (i.e., number of lanes) and work zone characteristics (i.e., presence and type of barrier or type of closure) were coded using the forward roadway view. Around 42% of observations were on 4-lane facilities, 53% were on multi-lane facilities and 5% were on 2-lane or other (i.e., on-ramp). Around 47% occurred in locations with one or two shoulders closed and 27% occurred in locations where one or more lanes were closed. The remaining events occurred upstream of the actual work or in a work zone with no closures.

Barrels were present at 51% of back of queue locations and concrete median was present at 29%. Only a few observations were present with other types of barrier (i.e., cones, delineators) so they were combined into one category and were present 10% of the time. Additionally, 10% of back of queue events occurred in a location with no barrier present. Environmental conditions were also coded which included time of day (81% day, 19% night/dusk/dawn) and dry (88%) versus wet (12%).

Several driver/vehicle variables were recorded for each BOQ event included the following:

- **Reaction time:** time stamp where the lead vehicle began braking or slowing which suggests a need for the following (subject SHRP2 NDS driver) to also react. The lead vehicle may also have been stopped when the subject vehicle encountered the back of queue and in this case the point at which the subject vehicle would have been able to notice the queue was recorded as reaction time.
- **Incident time:** time stamp when the following subject vehicle took action in response to the lead vehicle (i.e., braking, slowing)
- **Average Speed:** average speed for subject vehicle 10 second prior to reaction time
- **Maximum speed:** maximum speed for subject vehicle 10 second prior to reaction time
- **STD:** standard deviation of speed for subject vehicle 10 second prior to reaction time
- **Max acceleration:** the maximum acceleration (recorded in g's) for subject vehicle 10 second prior to reaction time
- **Following:** a subjective measure of following behavior for subject vehicle
  - Following closely (< 2 seconds)
  - Following (2 to 3 seconds)
  - Not following (> 3 seconds)

Driver characteristics (e.g., age, gender, years driving, number of violations) were provided for each driver by VTTI. Analysts at VTTI coded glance location and distraction for the set of back of queue driving events. This included identifying glances away from the driving task. Distraction was coded in the form of secondary tasks. As a result, distractions were recorded when they involved a glance away from the forward roadway. Additionally, cell phone use was identified when possible and noted. Unlike distraction, cell phone use did not need to be associated with a glance away from the driving task. Distraction, glance data, and cell phone were coded for the six seconds before and six seconds after reaction time. The 6 second window was based on perception reaction time and an assessment of time needed for a driver to execute an evasive maneuver. Distraction, glance, and cell phone were joined to the corresponding time series trace using time stamps. The following variables were reduced:

- **Cellphone:** subject driver used cellphone at any point 6 seconds before reaction time to 6 seconds after reaction time regardless of glance location
- **Glance:** Subject driver was engaged in a glance of 1 or more seconds away from the forward roadway within the period 6 seconds before reaction time to 6 seconds after reaction time.
- **Cell Distraction:** Subject driver was engaged in a cell phone task (reaching, texting, talking) which involved a glance away from the forward roadway within the period 6 seconds before reaction time to 6 seconds after reaction time

A simplistic comparison of the data indicates 28% of drivers involved in a back of queue SCE were using a cell phone compared to 5% of driver in the baseline as shown in Figure 5.2.

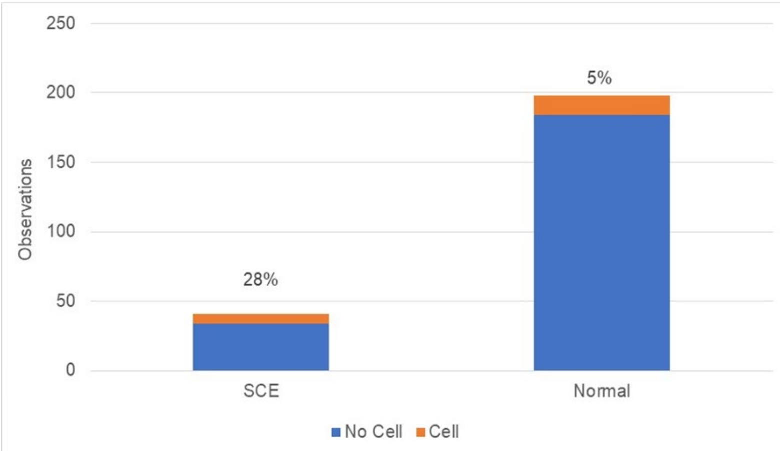


Figure 5.2. Relationship between cell phone use and safety critical events

Hence, drivers involved in an SCE were more than 5 times more likely to be engaged in a cell phone task as those involved in a "normal" back of queue event.

5.3 METHODOLOGY

Safety critical events (i.e., crash, near-crash, and conflicts) are typically classified by VTTI using as having a threshold deceleration of 0.5 g or higher occurs and/or an evasive maneuver occurs. Other thresholds were investigated (i.e., 0.4 g) to identify safety critical events. Klauer et al. (2009) evaluated different braking thresholds in the 100 Car Naturalistic Driving Data. They categorized driving behavior as safe (−0.30 to −0.39), moderately safe (−0.40 to −0.49), and unsafe (−0.5 to −0.59). Kusano and Gabler (2011) evaluated rear-end crashes from the National Automotive Sampling System / Crashworthiness Data System. They found an average deceleration of 0.52 g. Another study by Aoki et al. (2010) conducted a simulator study where volunteers were subjected to a crash situation. The result from this study also showed an average braking deceleration of 0.39 g. Several other studies have defined hard braking events as ≥ 0.45 g (Simons-Morton et al. 2009, McGehee et al. 2007, Wierwille et al. 2005). Wood and Zhang 2017 defined crash and near-crash rate of 0.41 g and 0.45 g.

Since some variability existed as to the threshold between a near-crash and regular driving event, three different models were developed. The response variable was first defined as a safety critical event using of the coding of crash/near-crash defined by VTTI. Models were also developed using an instance of 0.3 g or 0.4 g as the threshold between safety critical events and baseline events. This increased the sample size of cases meeting the criteria for safety critical events as well as increasing the number of predictor variables associated with the additional cases. However, use of the different thresholds resulted in similar results as the first model. Since the definition used by VTTI is more consistent, that definition was used and SCE were defined as a crash, an event with a deceleration of 0.5 g or higher, or an event with an evasive maneuver. This resulted in 46 safety critical events (SCE) and 283 "normal" events which are used as controls.

A review of the data indicated that several drivers were represented multiple times in both SCE and normal events. This could have been accounted for using a repeated measures variable for drivers.

However, most drivers only had one observation and an assessment of initial model results suggested the small sample of drivers with multiple observations was skewing results. Consequently, drivers with more than 2 events were randomly sampled and only 2 events per driver were ultimately included in the model. This resulted reduced the sample to 219 “normal” traces with 43 SCE representing 209 unique drivers.

A Mixed-Effects Logistic Regression model was developed with probability of a SCE as the response variable. Various models were tested using predictor variables which included driver age, driver gender, driver distraction (“Distraction”), cell phone use (“Cellphone), distraction involving a cell phone (“Cell Distraction”), maximum speed before reaction, average speed, roadway type, following behavior, type of work zone (i.e. no closures, shoulder closure, lane closure), type of barrier (i.e. concrete, barriers), and time of day.

A mixed effects logistic regression model was developed to assess the relationship between probability of an SCE and roadway, driver, and work zone characteristics. The variable Y_i was the event type for the i-th trace. For the event type model, the possible values are Y_ij=0 if the drive had a “normal reaction” and Y_ij if it was a “SCE.”

That is,

$$Y_i \sim Bernoulli(p_i)$$

where the probability of and SCE, p_i, is associated to the independent variables through the logit function:

$$logit(p_i) = X_i^T \beta,$$

where X_i are the covariate values, and β the fixed parameters. The logit function is defined as

$$logit(p) = \log\left(\frac{p}{1-p}\right).$$

The logit function facilitates the interpretation of the parameters β, since it represents the log-ratios. The vector β has a size of $k+1$ representing the parameter estimates for the k covariates plus the intercept estimate. If the j-th entry represents a binary variable (e.g., sex: 1 = male, 0 = female) and $\exp(\hat{\beta}_j) = 1.02$, then it means that obsevations with the presence of such variable are 2% more likely to have a near crash reaction.

For both models, stepwise forward selection was used. The selection criterion was the Akaike information criterion (AIC).

5.4 RESULTS

The final best model included whether a driver glanced away from the roadway task at least once for 1 or more seconds (Glance +1), following status (Following), and average speed (Avg_Spd) in the 6 seconds before the reaction time. The latter variable was included through a spline to allow it some flexibility. Model fit statistics are provided in Table 5.1.

Table 5.1. Anova of reaction type model

Term	F-statistic	df	p-value
Glance +1	5.7402	1	0.0166
Following	11.0798	2	0.0039
Avg_Spd	5.0076	2	0.0818

Model results are shown in Table 5.2.

Table 5.2. Estimates of reaction type model

Variable	Estimate	Std. Error	z value	Odds Ratio	Pr(>|z|)
(Intercept)	-0.7453	1.1999	-0.6212		0.5345
Glance +1	1.3339	0.5467	2.4397	3.80	0.0147
Following	-0.3172	0.6054	-0.5239	0.73	0.6003
Following Closely	1.0698	0.5615	1.9052	2.91	0.0568
bs(before_react_avg_speed, degree = 2)1	-1.3995	2.2424	-0.6241	0.25	0.5326
bs(before_react_avg_speed, degree = 2)2	-2.4256	1.1141	-2.1772	0.09	0.0295

As noted in Table 5.2, involvement in an SCE was 3.8 more likely if the driver was engaged in a glance away from the roadway task of 1 or more seconds (p = 0.0147). When a driver is following closely (< 2 seconds) they are 2.91 times more likely to be involved in an SCE (p = 0.0568) than when not following. Drivers following another vehicle (within 2 to 3 seconds) are less likely to be involved in an SCE, but this difference was not statistically significant (p = 0.6003) and was only included in the model since other conditions for following were included.

The average speed of the subject driver was also significant. Since the relationship is non-linear, it was included as a spline, the odd ratios cannot be interpreted directly and are shown graphically in Figure 5.3.

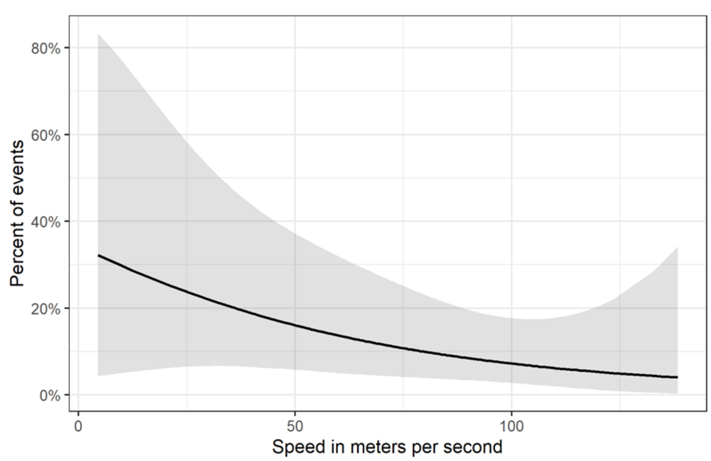


Figure 5.3. Relationship between average speed and probability of a back of queue safety critical event

As noted, drivers are more likely to be involved in a SCE at lower speeds than higher speeds. This is counterintuitive since in most cases, it is expected that higher speeds are related to back of queue crashes. The metric only reflects actual speed of subject vehicle. In most cases, work zone speed limit could not be determined. Nor could speed of prevailing vehicle be determined. As a result, while speed was included in the model, speeding could not be determined.

Cell phone use and cell phone distraction were not statistically significant. This may be due to small sample size. As noted in Figure 5-2 above, the sample of cell phone use was small for both SCE and normal events (n = 42).

5.5 CONCLUSION

5.5.1 Findings

The main purpose of this study was to assess driver behavior as they approached back of queues in work zones. Back of queue events related to work zones were identified in the SHRP2 NDS. The advantage to the SHRP2 NDS was the ability to review driver behavior before the event. Speed, cell phone use, distraction, and glance location were available and included in the analysis. Work zone characteristics such as type (i.e., lane or shoulder closure) and type of barrier present were also coded and used as covariates.

SCE were defined as crash, near -crash, or conflict using the definition utilized by VTTI which includes events where a deceleration of 0.5 g or higher and/or an evasive maneuver occurred. Models using 0.3 g and 0.4 g were also evaluated. This increased the sample size, but similar models resulted as for the original threshold and results were less conclusive. Using this definition, the model included 43 SCE and 219 "normal" events which were used as controls. The traces included representing 209 unique drivers.

A Mixed-Effects Logistic Regression model was developed with probability of a SCE as the response variable and driver and work zone characteristics as predictor variables. The final model indicated glances over 1 second away from the driving task and following closely increased risk of an SCE by 3.8 times and 2.9 times, respectively. Average speed was negatively correlated to crash risk. This is counterintuitive since in most cases, it is expected that higher speeds are related to back of queue crashes. In most cases, work zone speed limit could not be determined. Nor could prevailing speed of traffic be determined. As a result, the variable for speed only indicated the speed for the subject vehicle. Whether the vehicle was over the posted work zone speed limit or was traveling too fast for prevailing conditions could not be determined. As a result, there is likely a relationship between speeding and increased work zone safety risk which could not be determined from the model.

Cell phone use was not statistically significant (likely due to sample size). However, a simplistic analysis suggested drivers engage in an SCE were more than five times more likely to be engaged in a cell phone task than drivers involved in a normal back of queue event.

Results are consistent with other studies which have found following closely (Ullman et al. 2018, Rakotonirainy et al. 2017, Raub et al. 2001, Dissanayake and Akepati 2009) as a contributor to rear-end crashes. Additionally, studies have indicated that glances away from the roadway task and cell phone use increase crash risk in general (Klauer et al. 2006, Fitch et al. 2013, Atwood et al. 2018). Human factors research in simulated work zones has shown that drivers talking even hands-free were slower to respond, narrowed their eye scanning behavior, and were less likely to check their mirrors in a lane change (Muttart et al. 2007) suggesting a greater likelihood of crashes in work zones when talking on the phone, even hands-free.

5.5.2 Implications

The study findings can assist transportation agencies in addressing driver behaviors which impact back of queue conflicts. First, the study found activities which engage the driver's attention away from the roadway task for 1 or more seconds increased the likelihood of a back of queue safety critical event. This includes cell phone activities such as dialing and texting. Additionally, although not statistically significant, there was some evidence that cell use in use in general increased risk. The analyses also reinforce the concept that drivers engaged in glances away from the roadway tasks or cell phone tasks drove differently in work zones. Coupled with the body of work that has indicated distraction and cell phone use to negatively impact driver behavior, the efficacy of hands free or cell phone laws in work zones is reinforced.

Aggressive driver behavior, in particular speeding and following closely, have also been shown to contribute to rear-end crash risk in work zones. The role of following closely was confirmed by this study. Speeding and following closely may be addressed by QWS. Other countermeasures such as dynamic speed feedback signs or enforcement may also be effective for these types of behaviors.

5.5.3 Limitations

Several limitations were present in the study. The main limitation was sample size. Several thousand traces through work zones were reviewed for a related project and when present a back of queue event was flagged. Even with this quantity of data, the number of back of queue events was small. This resulted in only slightly more than 220 back of queue events. Limited sample size may have impacted the ability to identify relationships. As noted, cell phone use was more than twice as likely to occur in SCE than for normal back of queue events, but the impact was not shown to be statistically significant in the model. Distraction may also be correlated to back of queue SCE but there were not sufficient distractions to pick up a relationship. Glances away from the forward roadway included glances away with an associated distraction as well as just glances away but the impact of distraction alone could not be confirmed.

Another limitation is that glance location in the SHRP2 data is coded from driver head position rather than use of eye tracking devices. It is only possible to identify glances to general locations rather than to specific objects. Consequently, it was not possible to determine what drivers were looking at. It would have been insightful to determine whether drivers were distracted by work zone elements, such as workers.

CHAPTER 6: EVALUATION OF SPEED PROFILES IN WORK ZONES

Work zones make up a small portion of vehicle miles travelled but account for almost 2% of roadway fatal crashes in the US. In addition to drivers and passengers killed or injured, 132 work zone worker fatalities occurred in 2017 and 67% of highway contractors report motor vehicles having crashed into their construction work site. As a result, addressing work zone crashes is critical for both the traveling public and highway workers.

The SHRP2 Naturalistic Driving Study was used to evaluate the impact of various work zone and driver characteristics on speed selection. Speed was used as a safety surrogate since crashes and near-crashes were rare events in the SHRP 2 data. A set of active work zones on 4-lane and multi-lane roads were identified and time series data obtained for a range of drivers. A profile of vehicle speeds was developed at five points within the work zones (500 and 250 m upstream, at the work zone start point, 250 and 500 m downstream).

6.1 DATA

Time series traces (879) representing 407 unique drivers over 112 different work zones on multi-lane and 4-lane roadways were evaluated. Speed profiles at five points upstream and within work zones were developed and compared across relevant characteristics using a multivariate regression model. The model fit a speed profile model for each section simultaneously, creating a speed profile over the 5 points. Separate models were developed for work zones on 4-lane and multi-lane roadways.

Results for the 4-lane model indicate the work zone configuration, combination of median type upstream and barrier type within the work zone, glances away from the driving task over 1 second, and cell phone use were statistically significant. The same variables were statistically significant for the multi-lane model, but time of day and weather conditions were also relevant.

6.2 METHODOLOGY

Initial analyses were conducted which indicated significant differences exist between speeds on multi-lane versus 4-lane roadways. As a result, the two roadway types were modelled separately. Instant speed was modelled for five equally spaced sections over the upstream and downstream portion of each work zone. Data were sampled at 5 intervals: 500 meters (m) and 250 m upstream of the start of the work zone; at the point where the work zone started, and at 250 and 500 meters downstream of the start of the work zone. Work zone time series events were selected which spanned all 5 of the selected points. This resulted in 879 unique time series traces over 112 different work zones with 407 unique drivers.

Speed was averaged for a 25-meter window at each point. This averaging was done since some noise is present in the data and this prevented selection of an unrealistic high or low speed. The response variable was speed at each point. The models included predictor variables noted in Tables 6.1 and 6.2 for the 4-lane model and Tables 6.3 and 6.4 for the multi-lane model.

Table 6.1. Covariates evaluated in 4-lane model

Variable	Description
Environmental	Day/not raining = 248; night/not raining = 74; day/raining = 29; night/raining = 7
Work zone type	Left lane and right shoulder closed = 41, Left lane closed = 105, Left or right shoulder closed = 141, Right lane closed = 71
Median/barrier	Concrete/Concrete = 91, Concrete/ Other = 137, Other/Concrete = 61, Other/Other = 69
Glances 1+ second	0 = 203, 1+ = 78
Cellphone	no = 231, yes = 50
Cellphone	no = 231, yes = 50

Table 6.2. Description of speed statistics for 4-lane model

Variable	Summary
500 m upstream	min = 7.6, mean = 26.6, max = 34.2, std = 3.6
250 upstream	min = 4.8, mean = 26.2, max = 34.4, std = 3.8
WZ start	min = 9.3, mean = 25.7, max = 34.2, std = 3.7
250 m downstream	min = 8.8, mean = 24.9, max = 34.4, std = 3.8
500 m downstream	min = 9.3, mean = 24.6, max = 34.4, std = 3.8

Table 6.3. Covariates evaluated in multi-lane model

Variable	Tally
Environmental	Day/not raining = 363; night/not raining = 108; day/raining = 34; night/raining = 18
Work zone type	Left lane and right shoulder closed = 68, Left lane closed = 181, Only any shoulder closed = 235, Right lane closed = 39
Median/barrier	Concrete/Concrete = 199, Concrete/Other = 116, Other/Concrete = 77, Other/Other = 131
Glances 1+ second	0 = 348, 1+ = 69
Cellphone	no = 349, yes = 68

Table 6.4. Description of speed statistics for multi-lane model

Variable	Summary
500 m upstream	min = 4.1, mean = 27.6, max = 38.9, std = 5.4
250 m upstream	min = 4.5, mean = 27.7, max = 38.8, std = 5.1
Start of work zone	min = 3, mean = 27.3, max = 37.1, std = 5.3
250 m downstream	min = 4.9, mean = 27.1, max = 37.5, std = 5.1
500 m downstream	min = 5.2, mean = 26.9, max = 37.8, std = 5.2

Each predictor variable was examined, and several related variables were combined. For instance, time of day and weather were categorized as day/not raining, day/raining, night/not raining, and night/raining.

Several barrier types were present (i.e., cones, delineators, barrels) but samples sizes for some were smaller and speeds appeared similar for these types of barriers. As a result, barrier type in the work zone was categorized as concrete barrier or other. Similarly, median type upstream of the work zone was categorized as concrete barrier or other which included all other types of divided median such as grass or flush painted. Concrete/concrete indicated a concrete median barrier upstream of the work zone as the regular median and concrete barrier within the work zone. Other/Other which indicated grass, flush, or other type of median upstream and cones, barrels, delineators, or other type of barrier within the work zone.

Work zone configuration was categorized by type of lane or shoulder closures. Data were similar for all work zone configurations, which included right lane closures. For instance, they included a right lane closed or a right lane and left shoulder closure (used category of "right lane closed"). Differences were noted for left lane closures and left lane closures which also include a closure of the right shoulder. As a result, they were retained as distinct categories.

Separate models for four-lane and multi-lane roads were developed using a multivariate normal regression with mixed effects. The multivariate regression fit a speed model for each section simultaneously, creating a speed profile over the 5 points. This allowed speed to be compared between points and among variables. The predictor variables are computed trace wide. As a result, variables such as distraction or work zone type are included for the entire section modeled rather than for each point where speed was computed.

The "mixed effects" alludes to the fact that there are two types of variables, fixed effects, and random effects. The fixed effects are the variables of interest while the random effects are grouping variables to take dependency into account. The random effects for these models are driver ID and work zone ID. The multivariate normal model with mixed effects is given by the following equation:

$$Y_{ijk}^{(m)} = X_i^T \beta^{(m)} + \eta_j^{(m)} + \nu_k^{(m)} + \epsilon_{ijk}^{(m)},$$

for $m = 1, \dots, 5$. The vector $Y_{ijk} = (Y_{ijk}^{(1)}, \dots, Y_{ijk}^{(5)})$ is the instant speed of the i-th trace of the j-th driver in the k-th work zone at the five equally spaced sections: 500 m upstream, 250 m upstream, work zone start, 250 m downstream, and 500 m downstream. The transposed vector of size p, X_i^T, represents the p covariates (common for all five sections). The effect vectors, $\beta^{(m)}$ of size p have the usual interpretation of linear regression. For example, if the q-th variable ($q \leq p$) represents use of cellphone, then, if $\hat{\beta}_p^{(2)}$ were equal to 0.8, then the presence of cellphone use would be associated to an increase of 0.8 mps at the second section, that is, at 250 m upstream (the superindex indicates the work zone section).

The random terms, $\eta_j^{(m)}, \nu_k^{(m)}, \epsilon_{ijk}^{(m)}$, are independent for every i, j, k. The random effect corresponding to the driver, $\eta_j = (\eta_j^{(1)}, \dots, \eta_j^{(5)})$ is independent from the random effect introduced by the work zone random effect, $\nu_k = (\nu_k^{(1)}, \dots, \nu_k^{(5)})$, which are jointly independent from the random error $\epsilon_{ijk} = (\epsilon_{ijk}^{(1)}, \dots, \epsilon_{ijk}^{(5)})$. The entries of the vectors η_j, ν_k, and ϵ_{ijk} need not be independent.

The regression was fit in R (version 4.0.0) with the Rpackage "brms" (version 2.13.0), which is a Bayesian approach. All the priors were non-informative. The 6000 MCMC chains were extracted and the warm-up threshold was set at 3000 samples. Convergence was assessed with the R value and trace plots and model fit was evaluated using posterior predictives.

6.3 RESULTS FOR FOUR-LANE WORK ZONES

Parameters for the best fit model for work zones on four-lane roadways are provided in Tables 6.5 through 6.8.

Table 6.5. Fixed effects for 4-lane speed profile model

Parameter	Upstream 500 m	Upstream 250 m	Wz start	Downstream 250 m	Downstream 500 m
Intercept	26.04 (24.49, 27.56)	26.39 (24.86, 27.94)	26.15 (24.6, 27.64)	26.32 (24.8, 27.83)	26.26 (24.79, 27.79)
Wz config: Left lane closed	-0.55 (-2.01, 0.86)	-0.79 (-2.24, 0.59)	-0.78 (-2.19, 0.6)	-1.87 (-3.32, -0.43)	-1.5 (-3.01, -0.07)
Wz config: Shoulder closed	-0.94 (-2.45, 0.56)	-1.11 (-2.69, 0.39)	-0.22 (-1.71, 1.2)	-0.55 (-2.09, 0.94)	0.15 (-1.41, 1.59)
Wz config: Right Lane closed	0.21 (-1.4, 1.85)	0.33 (-1.3, 1.89)	-0.45 (-2.06, 1.07)	-2.47 (-4.13, -0.84)	-2.77 (-4.44, -1.25)
Median-Barrier: Concrete/Other	1.17 (-0.25, 2.61)	0.98 (-0.41, 2.43)	0.21 (-1.2, 1.63)	-0.09 (-1.53, 1.35)	-0.57 (-1.96, 0.87)
Median-Barrier: Other/Concrete	1.73 (0.23, 3.21)	0.66 (-0.87, 2.14)	-0.32 (-1.82, 1.14)	-0.9 (-2.36, 0.55)	-1.1 (-2.55, 0.4)
Median-barrier: Other/Other	0.6 (-0.88, 2.07)	-0.22 (-1.69, 1.26)	-0.66 (-2.08, 0.82)	-0.23 (-1.66, 1.2)	-0.76 (-2.21, 0.67)
Glances away over 1s: Yes	-1.07 (-2.03, -0.11)	-1.57 (-2.58, -0.58)	-0.97 (-1.88, -0.07)	-0.82 (-1.8, 0.2)	-0.8 (-1.75, 0.1)
Any cellphone: Yes	1.72 (0.63, 2.86)	1.54 (0.43, 2.73)	1.32 (0.29, 2.44)	1.08 (-0.08, 2.26)	0.85 (-0.21, 1.99)

Table 6.6. Random effects of 4-lane speed profile model

Random Effect	Upstream 500 m	Upstream 250 m	Wz start	Downstream 250 m	Downstream 500 m
Driver ID	0.23 (0.01, 0.6)	0.23 (0.01, 0.49)	0.17 (0.01, 0.45)	0.79 (0.41, 1.08)	0.22 (0.01, 0.6)
Work zone ID	0.69 (0.3, 1.1)	0.36 (0.01, 0.91)	1.51 (1.11, 2)	0.27 (0.01, 0.67)	1.02 (0.67, 1.44)

Table 6.7. Error estimate of 4-lane speed profile model

Upstream 500 m	Upstream 250 m	Wz start	Downstream 250m	Downstream 500 m
3.5 (3.2, 3.82)	3.65 (3.33, 3.97)	3.35 (3.08, 3.67)	3.63 (3.33, 3.96)	3.42 (3.13, 3.74)

Table 6.8. Residual correlations of 4-lane speed profile model

	Upstream 250m	Wz start	Downstream 250 m	Downstream 500 m
Upstream 500 m	0.9 (0.87, 0.92)	0.78 (0.73, 0.83)	0.62 (0.54, 0.7)	0.6 (0.52, 0.68)
Upstream 250 m		0.9 (0.88, 0.93)	0.78 (0.72, 0.83)	0.71 (0.65, 0.77)
Work Zone Start			0.89 (0.85, 0.92)	0.8 (0.75, 0.84)
Downstream 250 m				0.92 (0.9, 0.94)

Results are also presented in graphical form for ease of interpretation. Co-variates that resulted in the best fit model included type of work zone, type of barrier, glance behavior, and cell phone use.

As noted in Figure 6.1, work zones with both a left lane and right shoulder closure resulted in the least variation of speeds as drivers progressed through the work zone.

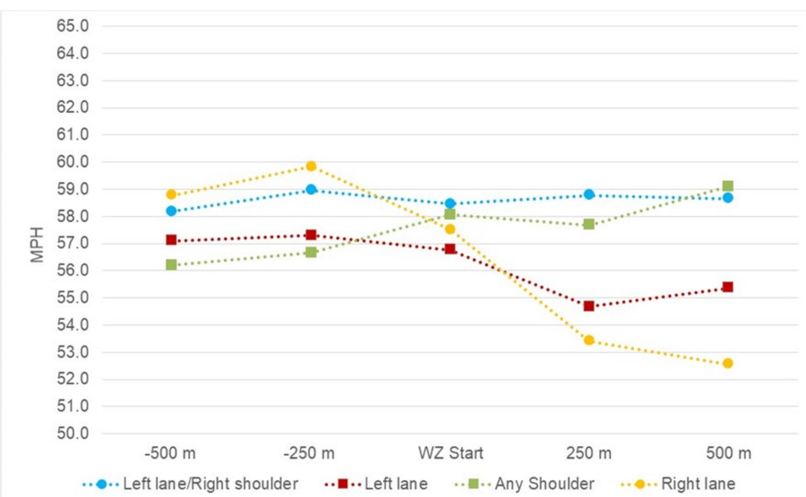


Figure 6.1. Speed by type of work zone closure for work zones on 4-lane roadways

The speed at any point varied between 58.2 to 59.0 mph. When a right lane closure was present, the estimated speed was also between 58.8 to 59.8 mph but dropped as the driver entered the work zone to between 52.6 and 53.4 mph. A similar situation was noted for a left lane closure, but speeds were slightly lower upstream of the work zone (around 57 mph) dropping to between 54.7 to 55.4 mph within the work zone. When only a shoulder closure was present (either right or left) initial speeds were around 56.2 to 56.7 mph but increased to up to 59.1 mph as the driver progressed through the work zone.

Median type was determined for the section upstream of the work zone and work zone barrier was determined for the section within the work zone. A number of barrier types were present (i.e., cones, delineators, barrels) but samples sizes for some types were small and speeds were similar for these types of barriers. As a result, barrier type in the work zone was categorized as concrete barrier or “other” which included cones, barrels, delineators, and panels. Similarly, median type upstream of the work zone was categorized as concrete barrier or “other” which included grass, flush, or other types of median. Concrete/concrete indicated a concrete median barrier upstream of the work zone as the regular median and concrete barrier within the work zone. Other/Other indicated grass, flush, or other type of median upstream and cones, barrels, delineators, or other type of barrier within the work zone.

As shown in Figure 6.2, the configuration with (Other/Concrete) had the highest speeds upstream and showed the largest decrease in speed from the upstream to work zone (up to 5.9 mph).

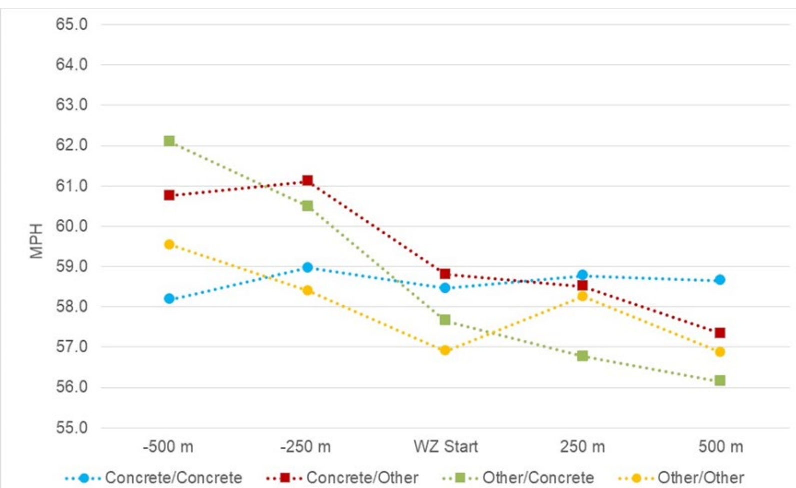


Figure 6.2. Speed by type of median upstream and barrier within the work zones for 4-lane roadways

Concrete/Other showed a 3.8 mph decrease and the configuration Other/Other exhibited a decrease of around 2.6 mph. The configuration with a concrete median barrier upstream and concrete barrier (Concrete/Concrete) within the work zone exhibited the least change in speed with differences of only around 0.5 mph from the upstream to downstream.

Whether a driver engaged in a glance away from the forward roadway of 1 or more seconds was also statistically significant in the model. As shown in Figure 6.3, drivers who engaged in one or more glances of 1+ second had speeds that were 2.4 to 3.5 mph lower than drivers who did not engage in glances.

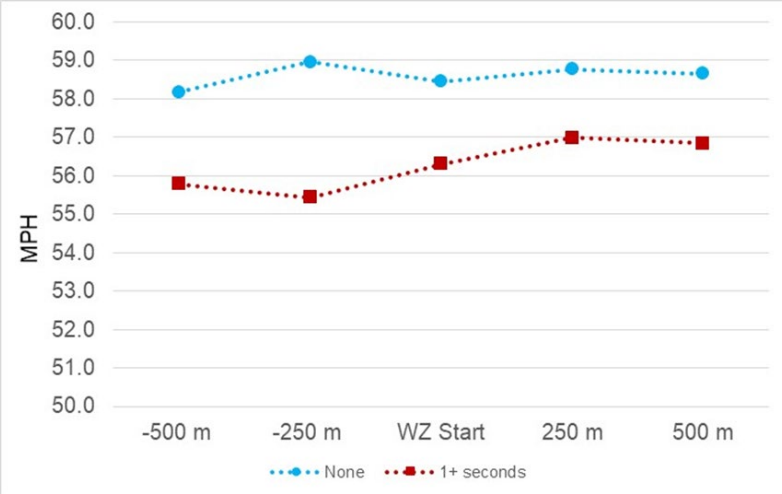


Figure 6.3. Speed by glances duration for work zones on 4-lane roadways

However, drivers who glanced away increased speeds within the work zone compared to drivers who did not glance away who had slight decreases in speeds (up to 1.6 mph) from the upstream to within work zone.

Cell phone use was also statistically significant in the final model for 4-lane roadways (Figure 6.4).

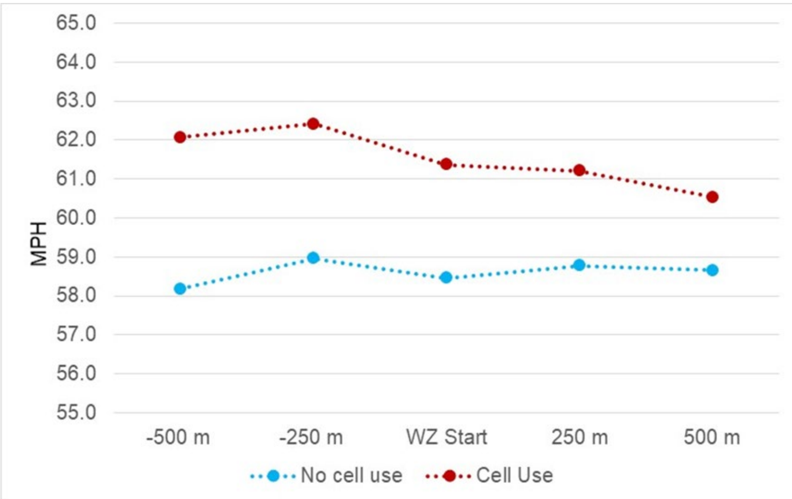


Figure 6.4. Speed by cell phone use for work zones on 4-lane roadways

Drivers who engaged in any cell phone task (talking, dialing, texting) whether or not it involved a glance away from the forward roadway travelled at higher speeds (up to 62.4 mph) than drivers who did not engage in a cell phone tasks who travelled around 58.2 to 59.0 mph. Drivers engaged in a cell phone task were more likely to decrease their speed from the upstream section to within the work zone (up to 1.9 mph) compared to those not engaged in a cell phone task who slowed less than 1 mph. Drivers not engaged in a cell phone task were traveling at speeds significantly below those engaged in a cell phone task. As a result, there may have been less need for a speed reduction as they encountered the work zone.

6.4 RESULTS FOR MULTI-LANE WORK ZONES

Parameters for the model for work zones on multi-lane roadways are provided in Tables 6.9 through 6.12.

Table 6.9. Fixed effects of multi-lane speed profile model

Parameter	Upstream 500 m	Upstream 250 m	Wz start	Downstream 250 m	Downstream 500 m
Intercept	26.83 (25.41, 28.31)	26.35 (25.04, 27.71)	24.83 (23.51, 26.22)	24.47 (23.19, 25.79)	24.55 (23.2, 25.92)
Time of Day/Weather: Night/Dry	0.04 (-1.1, 1.21)	0.19 (-0.89, 1.31)	0.54 (-0.6, 1.69)	0.64 (-0.43, 1.73)	0.86 (-0.24, 1.95)
Time of Day/Weather: Day/Rainy	-7.47 (-9.44, -5.52)	-8.14 (-9.93, -6.38)	-8.08 (-10, -6.24)	-7.94 (-9.83, -6.15)	-8.26 (-10.11, -6.41)
Time of Day/Weather: Night/Rainy	-0.59 (-2.91, 1.76)	-0.93 (-3.15, 1.27)	-0.74 (-3.1, 1.57)	-1.42 (-3.61, 0.72)	-0.75 (-2.98, 1.44)
Work zone configuration: Left lane closed	0.97 (-0.54, 2.42)	1.4 (-0.06, 2.8)	1.95 (0.45, 3.39)	1.43 (0.08, 2.76)	1.07 (-0.34, 2.49)
Work zone configuration: Only any shoulder closed	0.81 (-0.76, 2.32)	1.56 (0.1, 2.94)	2.69 (1.23, 4.13)	2.65 (1.26, 3.97)	1.99 (0.48, 3.41)
Work zone configuration: Right lane closed	-0.39 (-2.8, 2)	0.38 (-1.76, 2.68)	2.1 (-0.25, 4.4)	2.6 (0.44, 4.81)	2.08 (-0.18, 4 .38)
Median/Barrier: Concrete/Other	0.77 (-0.69, 2.2)	0.21 (-1.15, 1.51)	-0.29 (-1.68, 1.09)	0.35 (-0.96, 1.6)	0.15 (-1.18, 1.51)
Median/Barrier: Other/Concrete	4.44 (2.95, 5.9)	4.64 (3.31, 5.97)	5.16 (3.78, 6.54)	4.97 (3.66, 6.28)	4.36 (2.92, 5.74)
Median/Barrier: Other/Other	0.76 (-0.6, 2.16)	1.02 (-0.25, 2.31)	1.46 (0.15, 2.79)	1.96 (0.74, 3.23)	2.52 (1.16, 3.8)
Glances away over 1s: Yes	0.37 (-0.94, 1.64)	0.45 (-0.78, 1.66)	0.84 (-0.47, 2.12)	0.85 (-0.36, 2.09)	1.09 (-0.15, 2.3)
Any cellphone: Yes	-2.22 (-3.51, -0.93)	-2.16 (-3.36, -0.95)	-2.26 (-3.5, -1.02)	-2.02 (-3.22, -0.83)	-2.19 (-3.39, -0.97)

Table 6.10. Random effects of multi-lane speed profile model

Random Effect	Upstream 500 m	Upstream 250 m	Wz start	Downstream 250 m	Downstream 500 m
Driver ID	0.23 (0.01, 0.56)	0.16 (0.01, 0.43)	0.15 (0.01, 0.41)	0.1 (0, 0.27)	0.26 (0.01, 0.58)
Work Zone ID	0.67 (0.39, 0.97)	0.33 (0.04, 0.59)	0.1 (0, 0.29)	0.14 (0, 0.34)	0.65 (0.37, 0.96)

Table 6.11. Error estimate of multi-lane speed profile model

Upstream 500 m	Upstream 250 m	Work Zone start	Downstream 250 m	Downstream 500 m
4.65 (4.36, 4.98)	4.4 (4.12, 4.71)	4.64 (4.35, 4.96)	4.38 (4.1, 4.68)	4.38 (4.1, 4.69)

Table 6.12. Residual correlations of multi-lane speed profile model

	Upstream 250 m	Work zone start	Downstream 250 m	Downstream 500 m
Upstream 500 m	0.95 (0.93, 0.96)	0.8 (0.77, 0.84)	0.74 (0.7, 0.79)	0.69 (0.64, 0.74)
Upstream 250 m		0.88 (0.86, 0.9)	0.81 (0.78, 0.84)	0.76 (0.71, 0.8)
Work Zone Start			0.93 (0.92, 0.95)	0.86 (0.84, 0.89)
Downstream 250 m				0.94 (0.92, 0.95)

Results are also presented in graphical form for ease of interpretation. Co-variates that resulted in the best fit model included type of work zone configuration, type of barrier, environmental conditions, glance behavior, and cell phone use.

As noted in Figure 6.5, work zones with a left lane closure (up to 62.3 mph) or shoulder closures (up to 62.5 mph) had the highest speeds upstream of the work zone.

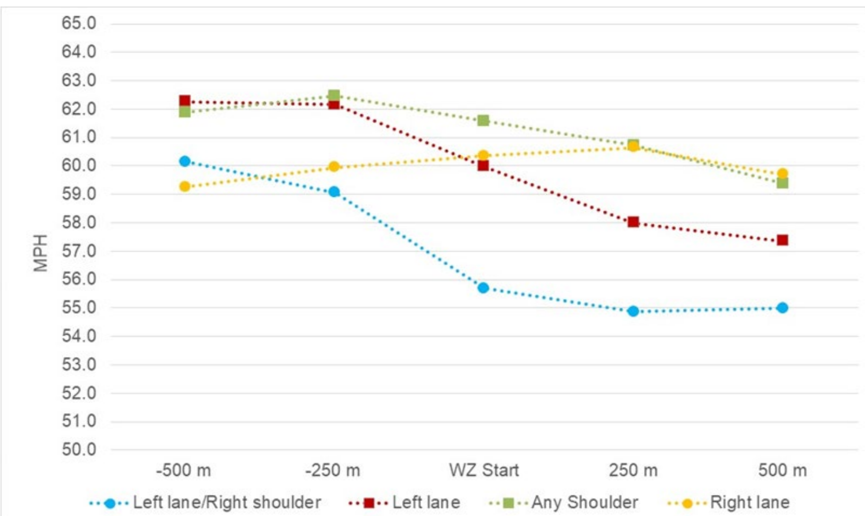


Figure 6.5. Speed by type of work zone closure for work zones on multi-lane roadways

Speeds decreased by up to 4.2 mph within the work zone for the left lane closure, but speeds only decreased by up to 1.7 mph for shoulder closures. When a left lane and right shoulder were closed, speeds were slightly lower upstream than a left lane closure only (around 60.1 mph) with decreases of up to 4.2 mph noted within the work zone. When a right lane closures was present speeds were slightly lower upstream than other configurations (up to 60.0 mph) but speeds within the work zone increased by up to 0.7 mph.

Median type upstream and work zone barrier within the work zone was also relevant. As noted in the description of the 4-lane models, barrier type was condensed to concrete barrier or “other barrier” and median was condensed to concrete median or “Other median.” As shown in Figure 6.6, the highest upstream speeds were noted for work zones with “Other” medians upstream and concrete barriers within the work zone with speeds up to 70.1 mph.

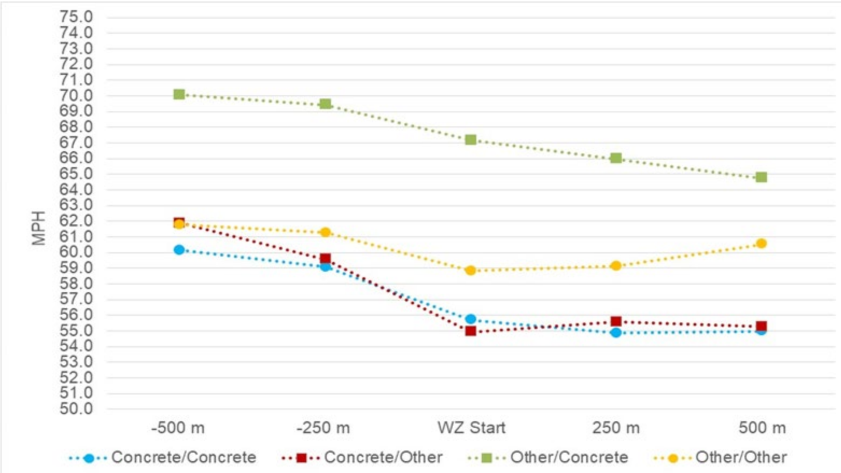


Figure 6.6. Speed by type of median upstream and barrier within the work zone for multi-lane roadways

Speeds decreased by up to 5.4 mph within the work zone. Speeds were lowest in the upstream section when work zones had a concrete median and concrete barrier within the work zone with speeds up to 60.1 mph upstream and decreases of up to 5.3 mph within the work zone. Work zones with a concrete median upstream and "Other" barrier within the work zone had speeds up to 61.9 mph upstream with decreases of up to 6.6 mph within the work zone. When "Other" median was present upstream and "Other" barrier was present within the work zone speeds were up to 61.8 mph upstream and the smallest speed decreases within the work zone were noted (up to 2.7 mph).

Whether a driver engaged in a glance away from the forward roadway of 1 or more seconds was also statistically significant in the model for multi-lane roadways. As shown in Figure 6.7, drivers who engaged in one or more glances of 1+ second had speeds that were around 1 mph higher than drivers who did not engage in glances.

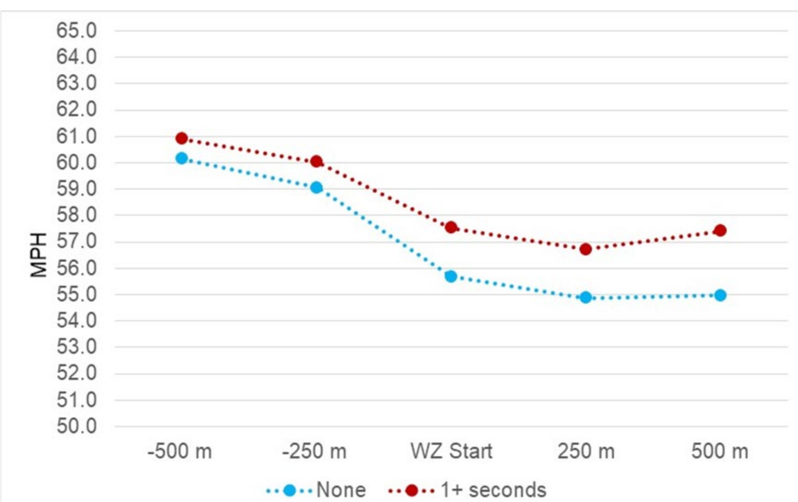


Figure 6.7. Speed by glances away from roadway tasks for work zones on multi-lane roadways

Both sets of drivers reduced speeds as they entered the work zone. However, drivers who glanced away for 1+ seconds had lower speed reductions (up to 4.2 mph) than drives who did not glance away (up to 5.3 mph).

Cell phone use was also statistically significant in the final model for multi-lane roadways (Figure 6.8).

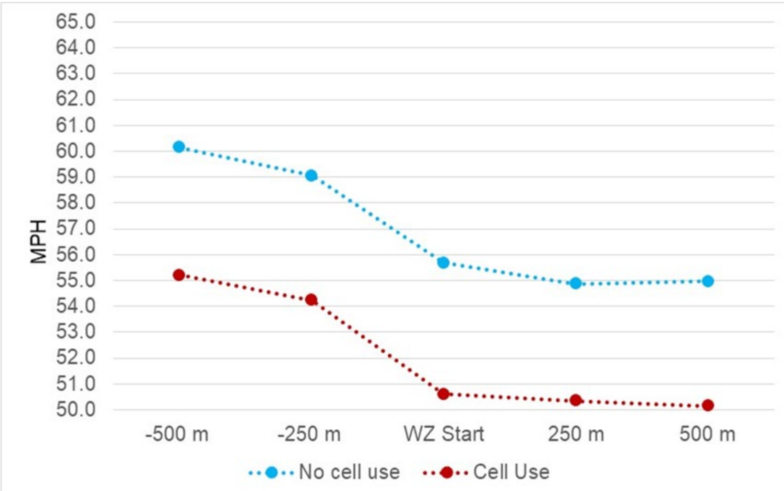


Figure 6.8. Speed by cell phone use for multi-lane work zones

Drivers who were not engaged in any cell phone task travelled at higher speeds (59.1 to 60.1 mph) than drivers engaged in a cell phone tasks who travelled 54.2 to 55.2 mph. Both sets of drivers decreased speed from the upstream section to within the work zone in a similar manner (5.1 mph for those using a cell phone and 5.3 for those not engaged in a cell phone task). This result was the opposite of that found for the 4-lane model where drivers engaged in cell phone tasks had higher speeds.

Environmental conditions were also noted in the model as being statistically significant (Figure 6.9).

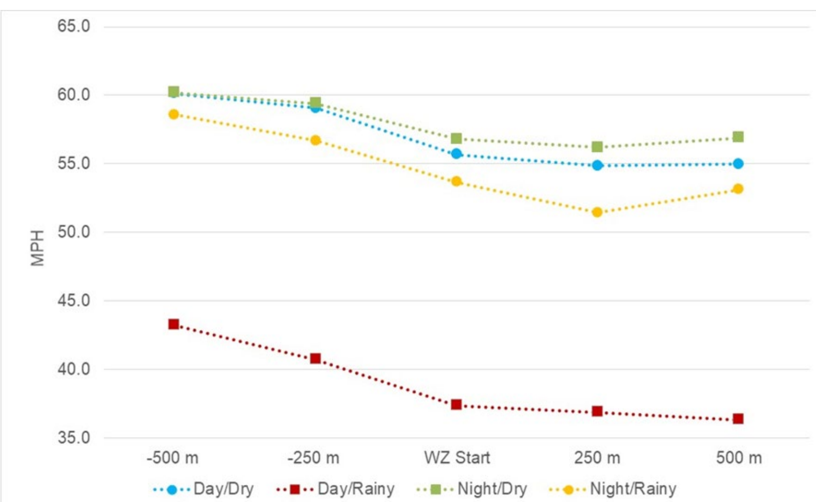


Figure 6.9. Speed by environmental conditions for multi-lane work zones

Four categories were used to describe conditions in terms of time of day and weather. Traces were coded as Day/Dry, Day/Rainy, Night/Dry, and Night/Raining. Time series events with adverse weather such as snow, ice, and heavy rain were not included in the model. Drivers behaved similarly for night and day when dry conditions prevailed. Upstream speeds were 59.1 to 60.2 mph with reductions within the work zone of up to 4.0 mph. Speeds upstream of the work zone were significantly lower during the day when rain was present that during night conditions with rain with speeds between 40.7 to 43.3 mph compared to 56.7 to 58.6 mph. Speed reductions during the day with rain were up to 6.9 mph compared to up to 5.5 mph for night with rain. Lower speeds and higher speed reduction during daytime rain events compared to similar night events may be due to higher volumes.

6.5 SUMMARY AND CONCLUSIONS

The main purpose of this study was to assess speed in work zones using the SHPR 2 NDS data. A set of active work zones on 4-lane and multi-lane roads were identified and time series data obtained for a range of drivers. A profile of vehicle speeds was developed at five points within the work zones (500 and 250 m upstream, at the work zone start point, 250 and 500 m downstream) and speed modelled using a multivariate normal regression with mixed effects. Separate models were developed for each type of roadway.

The best fit model for work zones on 4-lane roadways indicated work zone configuration, type of median/barrier, glance behavior, and cell phone use were significant. The best fit model for work zones on multi-lane roadways included the same variables, but environmental conditions were also relevant.

6.5.1 Work Zone Configuration

Work zone configuration included several lane or shoulder closure configurations. A summary of results is shown in Table 6.13.

Table 6.13. Summary of work zone configuration impacts on speed

Configuration	Highest speed upstream (mph)		Largest change upstream to within work zone (mph)	
	4-lane	Multi-lane	4-lane	Multi-lane
Left lane/right shoulder	59.0	60.1	-0.8	-4.2
Left lane	57.2	62.3	-2.5	-4.2
Right lane	59.8	60.0	-6.4	0.7
Any shoulder	56.7	62.5	2.4	-1.7

As noted, shoulder closures on 4-lane roadways resulted in speed increases from the upstream section to within the work zone. Additionally, as noted for multi-lane roadways, work zones with shoulder closures had the highest speeds upstream of the work zone with only small speed changes once they entered the work zone (up to 1.7 mph).

Left lane closures showed experienced the largest decreases in speeds from the upstream to work zone section for multi-lane roadways (around 4.2 mph), but higher speeds were noted when only a left lane closure was present (62.3 mph). Speeds upstream of work zones on 4-lane roadways with a left lane or left lane/right shoulder closure were similar. However, only moderate decreases were noted within the work zone (0.8 mph) while speed decreased by up to 2.5 mph for the left lane closure only.

The largest speed reductions for 4-lane roadways occurred when a right lane closure was present with decrease up to 6.4 mph noted.

As noted, driver speed is impacted by work configuration. Although, work zone configuration is not a speed management countermeasure, the results indicated some types of configurations are more likely to have higher speed profiles and less reductions as drivers enter the work zone. As a result, it suggests some configurations may need additional speed reductions measures.

6.5.2 Type of Barrier

Median type upstream and barrier type within the work zone was also relevant in both models. Results are summarized in Table 6.14.

Table 6.14. Impacts of median and barrier type on speed

Configuration	Highest speed upstream (mph)		Largest change upstream to within work zone (mph)	
	4-lane	Multi-lane	4-lane	Multi-lane
Concrete/Concrete	59.0	60.1	-0.5	-5.2
Concrete/Other	61.1	61.9	-3.8	-6.6
Other/Concrete	62.1	70.1	-5.9	-5.4
Other/Other	59.5	61.8	-2.6	-2.7

Speeds were highest in the upstream section for both 4-lane and multi-lane roadways when “Other” median type (which included grass, painted) was present in the upstream section and a concrete median barrier was present within the work zone.

Speeds were lowest in the upstream section for both roadway types when a concrete median was present upstream, and a concrete barrier was present in the work zone. But only minor changes from the upstream to work zone section resulted on 4-lane roadways (around 0.5 mph) while decreases up to 5.2 mph occurred in the work zones on multi-lane roadways.

The largest decreases in speed for both roadway types were present when a concrete median or barrier was present either upstream or downstream, but a different median/barrier type was present in the other section. Work zones on 4-lane roadways with a “Other” median type upstream and concrete barrier within the work zone saw a 5.9 mph decrease in speeds while on multi-lane roadways with concrete median upstream and other type of barrier within the work zone saw 6.6 mph reduction. In configurations with “Other” median type upstream and “Other” barrier type in the work zone, saw smaller decreases in speed (up to 2.7 mph for either roadway type).

As a result, having a concrete median/barrier in one area but not the other appeared to alter driver behavior the most in terms of reducing speed within the work zone. This may be due to having what feels like an abrupt change in vertical friction to drivers.

6.5.3 Glance Location and Cell Phone Use

Glance location was also relevant in both models. The predictor variable was the driver having one or more glances of 1 second or longer (1+ sec) away from the roadway task or no glances of this duration. Distraction was coded when they occurred in conjunction with a glance away from the roadway task. As a result, the number and duration of distractions was smaller than the sample of glances away from the forward roadway. As a result, distraction alone could not be detected in the models. Additionally, many researchers have indicated a glance of 2 or more seconds away from the roadway task are the most critical. However, the sample size for glances of 2 or more seconds was substantially smaller than glances of 1 or more seconds and could not be detected in the model.

The 4-lane model found drivers who engaged 1+ sec glances had speeds that were 2.4 to 3.5 mph lower than drivers who did not engage in glances. However, these drivers also increased speeds from the upstream section to within the work zone (up to 1.6 mph) compared to drivers who did not glance away who held speed relatively constant within the work zone. This may indicate drivers not attending to the roadway task become aware of the work zone later than drivers who are looking towards roadway tasks. It should be noted that only glance location could be determined. Inattention may manifest itself as glancing away from the roadway task, but inattention could not be measured.

Conversely, the multi-lane model indicated that drivers who engaged 1+ sec glances had speeds that were around 1 mph higher than drivers who did not engage in glances. Both sets of drivers reduced speeds as they entered the work zone. However, drivers who glanced away for 1+ seconds had lower speed reductions (up to 4.2 mph) than drives who did not glance away (up to 5.3 mph).

Drivers engaged in cell phone tasks traveled at higher speeds in work zones on 4-lane roadways compared to drivers not engaged in cell phone tasks. The exact opposite was noted for work zones on multi-lane roadways where drivers engaged in cell phone activities had lower speeds than those not engaged with a cell phone. Although opposite results are noted, they do suggest drivers engaged in cell phone activities behavior differently than those not engaged.

Results are consistent with other studies which have found glances away from the roadway task and cell phone impact driver behavior and increase crash risk in general (Klauer et al. 2006, Fitch et al. 2013, Atwood et al. 2018, Muttart et al. 2007).

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